Neutrino-nucleus Cross Section Measurements at the Spallation Neutron Source

Vince Cianciolo, ORNL
For the ν-SNS Collaboration
PANIC 2005 Satellite Neutrino Workshop
10/30/2005

Outline

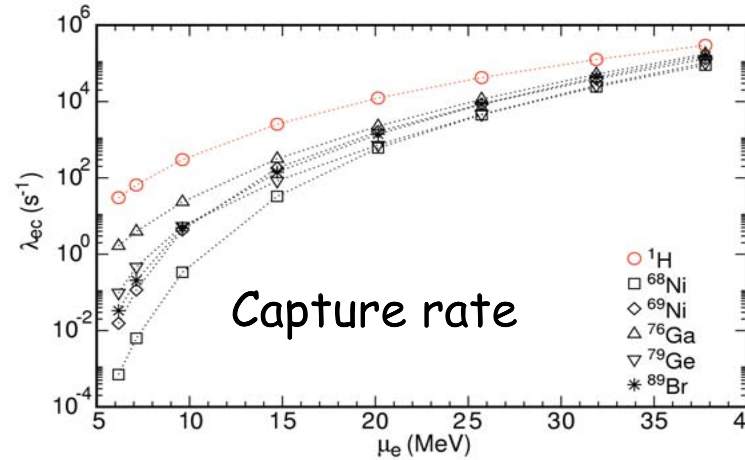
- Physics motivation
- Stopped-pion neutrinos and the SNS
- ν-SNS Facility
- Potential measurements and detectors
- Collaboration, cost, schedule, status

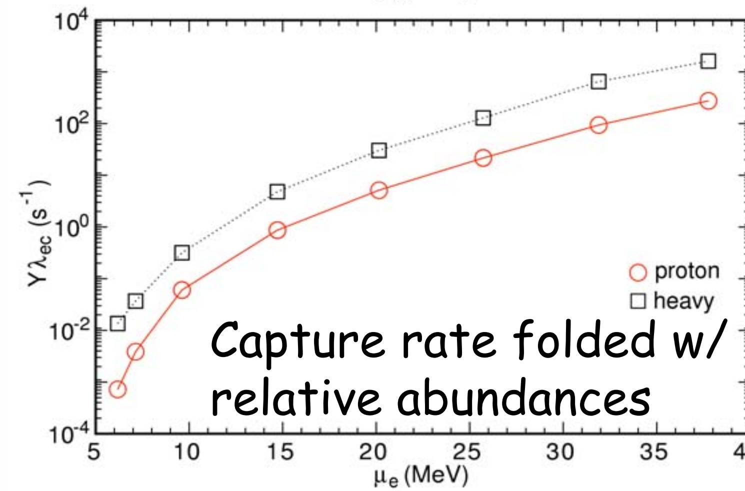
Core-collapse Supernovae

- Among the most energetic explosions in the Universe:
  - 10^{46} J of energy released
  - 99% carried by neutrinos
- A few happen every century in our galaxy, but the last one observed was over 300 years ago.
- Dominant contributor to galactic nucleosynthesis.
- Driven by the collapse of the iron core of a massive star, but the explosion mechanism is still not well understood.
- Neutrino/electron capture on heavy nuclei play an important role in all aspects of the core collapse supernova problem:
  - Explosion dynamics
  - Nucleosynthesis
    - Neutrino nucleosynthesis
    - Explosive nucleosynthesis
    - *r*-process
  - Neutrino detection

e^-/ν Capture During Core Collapse

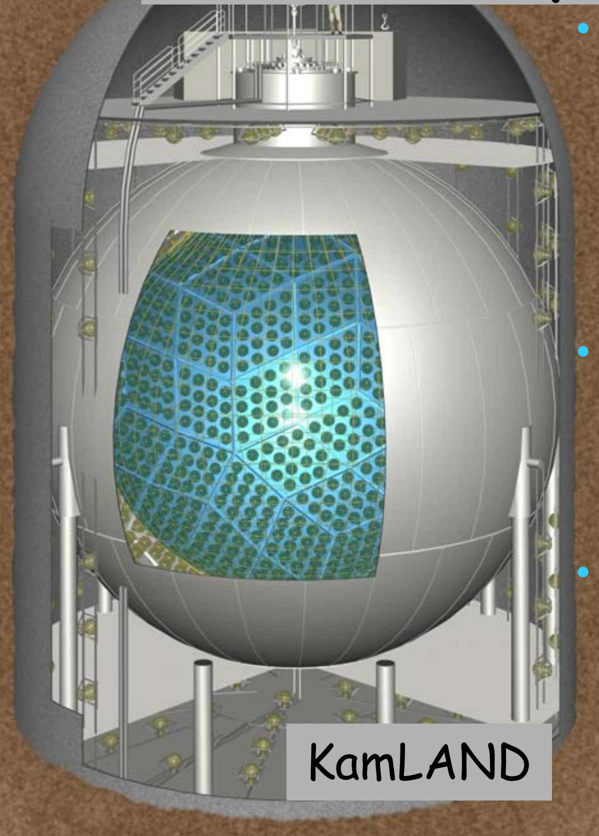
- Nuclei with A>50 dominate the composition in the stellar interior.
- e^- and ν capture on these nuclei are the dominant nuclear processes prior to core bounce.
- Recent calculations using rates that include effects of thermal unblocking and correlations show large differences in collapse behavior.



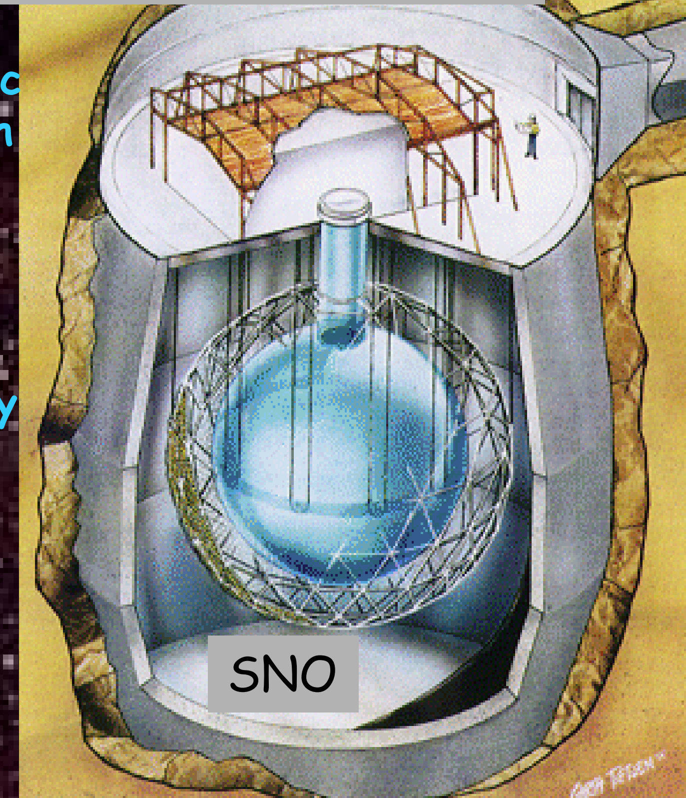


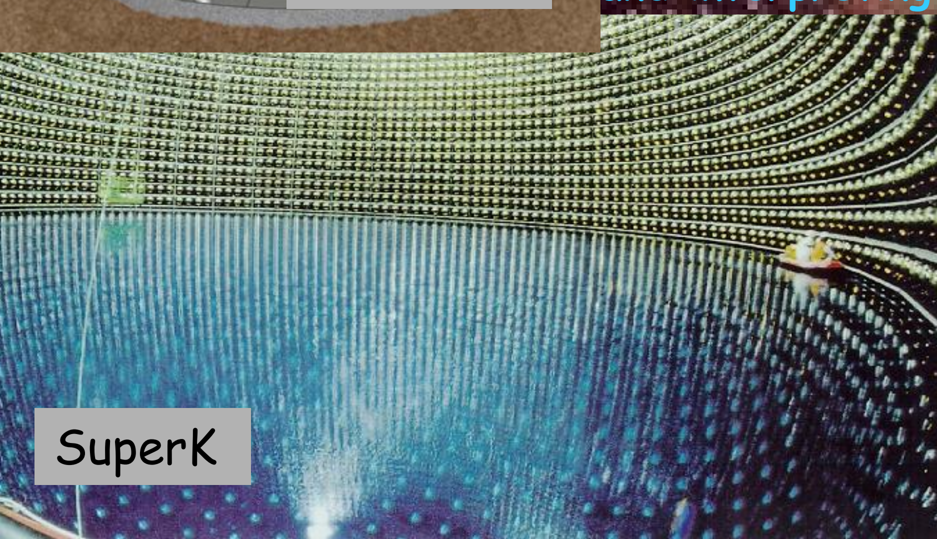
K. Langanke, E. Kolbe and D.J. Dean, Phys. Rev. **C63**, 32801 (2001).

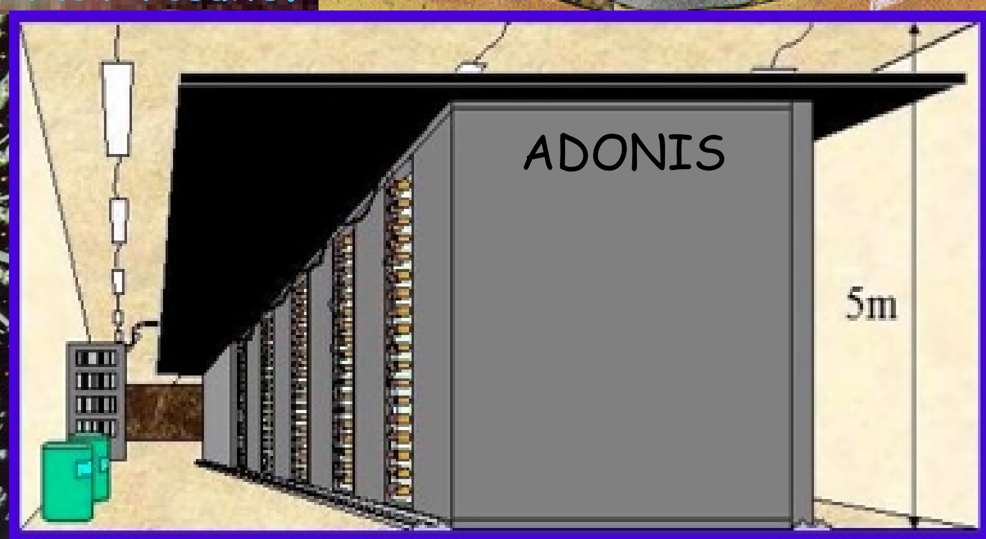
Supernova ν Observations



- Measurement of the neutrino energy spectra from a Galactic supernova will provide a wealth of information on the conditions in supernovae, neutrino oscillations, etc.
- When the next Galactic supernova occurs, we will likely observe it with several detectors using several nuclei.
- An accurate understanding of neutrino cross sections is important for designing supernova neutrino detectors and interpreting their results.



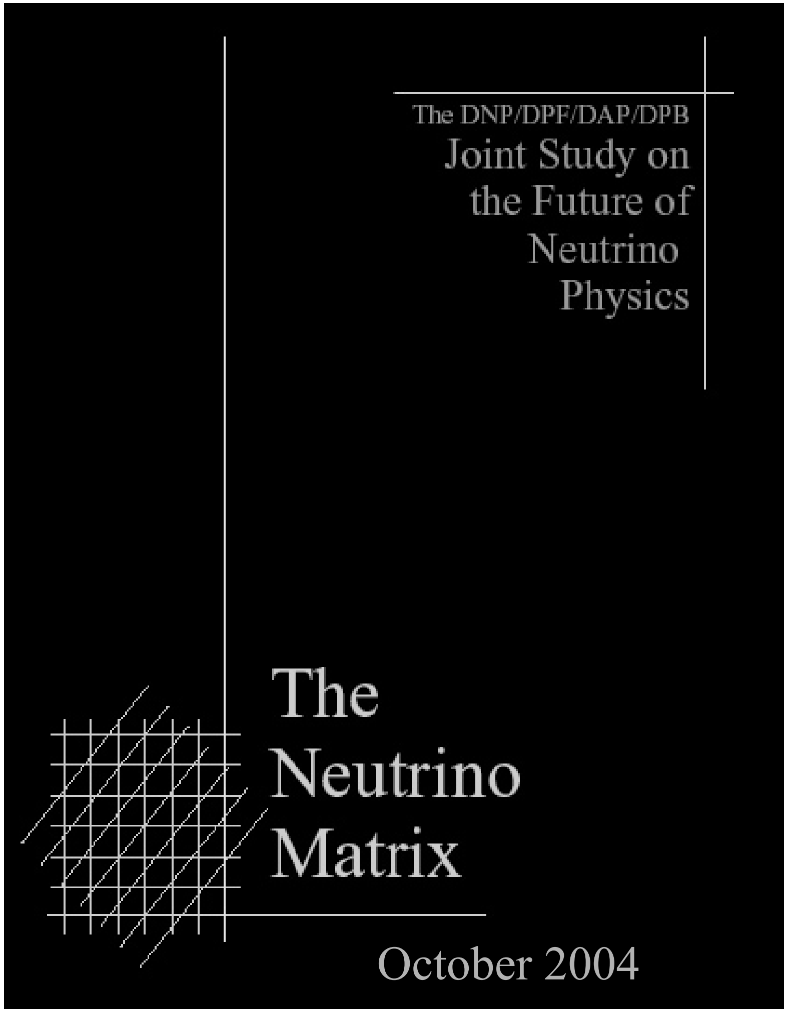




Physics For "Free" at the SNS

- The SNS allows definitive measurements of nuclear excitations that would be difficult to generate or analyze with any other type of experiment.
- It also provides a special opportunity to search for lepton flavor number violating processes due to the small $\bar{\nu}_e$ flux.
  - Nearly all π^- and μ^- are captured in the target.
  - The observation of $\bar{\nu}_e$ capture events in excess of the small flux expected from μ^- decay and other sources provides a sensitive signature for lepton flavor number violation.
- The shape of the ν_e spectrum from μ^+ decay at rest is sensitive to scalar and tensor admixtures to pure V-A interactions.
- Near detector for OSCSNS (R. Van de Water talk yesterday)

- These topics can all be studied with the proposed detectors with the same data sets used to make cross section measurements.



Recommendations Section

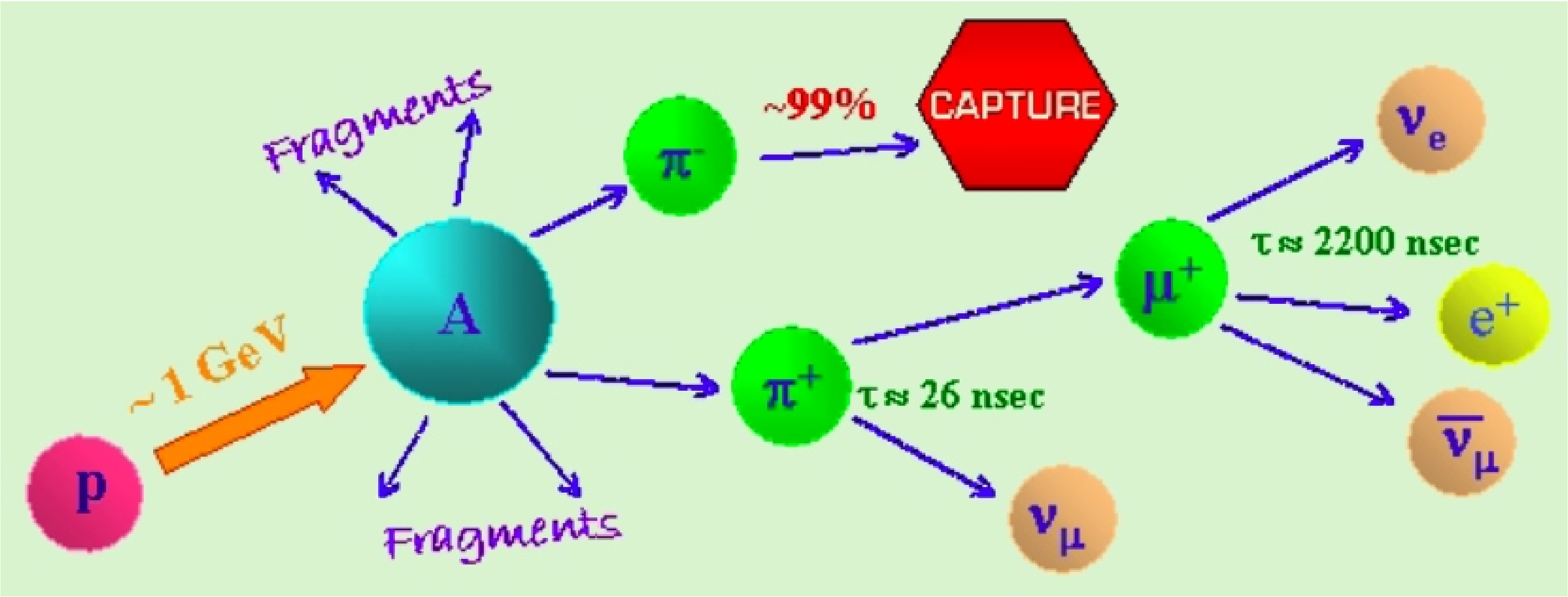
Turning to the recommendations for the future, we preface our remarks by drawing attention to some basic elements in common:

1. In every instance the need for suitable underground detector facilities emerges. A successful neutrino program depends on the availability of such underground space.
2. The precise determination of neutrino cross sections is an essential ingredient in the interpretation of neutrino experiments and is, in addition, capable of revealing exotic and unexpected phenomena, such as the existence of a neutrino magnetic dipole moment. Interpretation of atmospheric and long-baseline accelerator-based neutrino experiments, understanding the role of neutrinos in supernova explosions, and predicting the abundances of the elements produced in those explosions all require knowledge of neutrino cross sections. New facilities, such as the Spallation Neutron Source, and existing neutrino beams can be used to meet this essential need.
3. It is important that at least two detectors worldwide should be operational which, in

Executive Summary

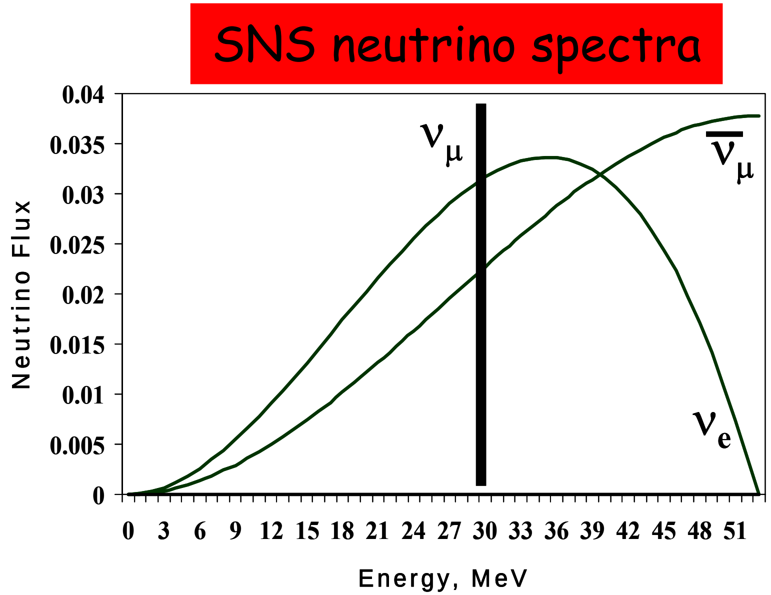
- Determination of the neutrino reaction and production cross sections required for a precise understanding of neutrino-oscillation physics and the neutrino astronomy of astrophysical and cosmological sources. Our broad and exacting program of neutrino physics is built upon precise knowledge of how neutrinos interact with matter.
- Research and development to assure the practical and timely realization of acceler-

Stopped Pion Decay

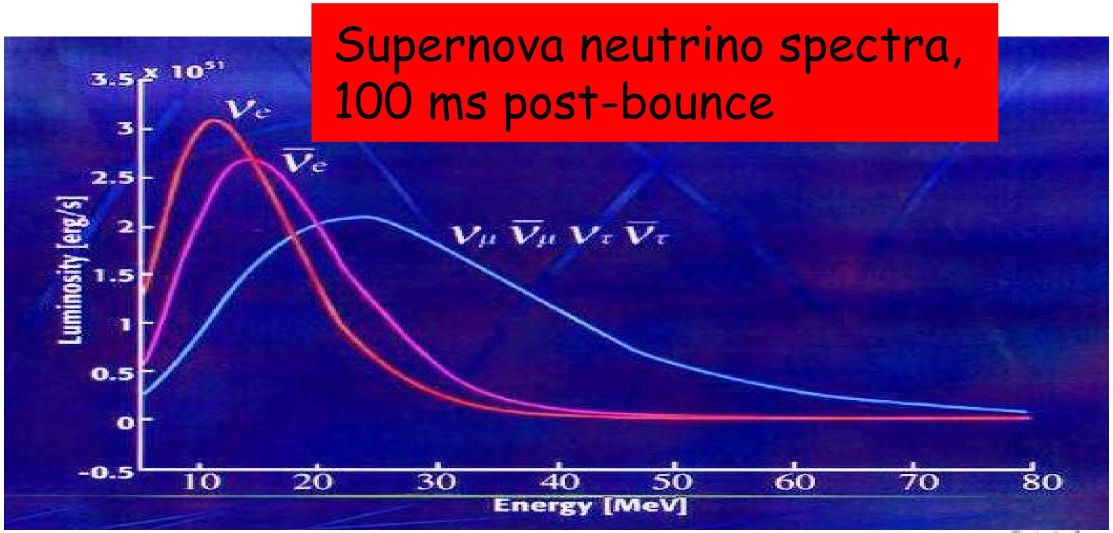


Energy Spectra

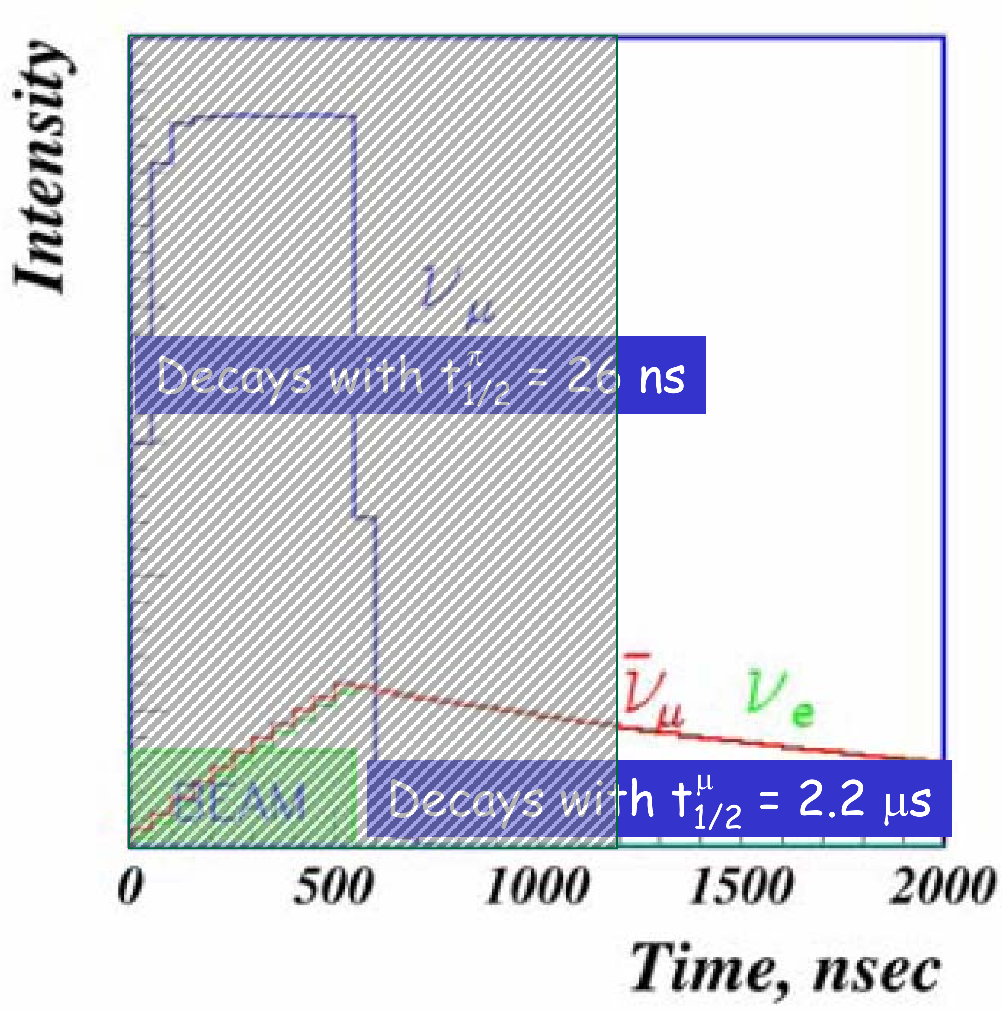
- Neutrino spectra at stopped-pion facilities are well-defined…



- And they have significant overlap with the spectra of neutrinos generated in a supernova explosion!



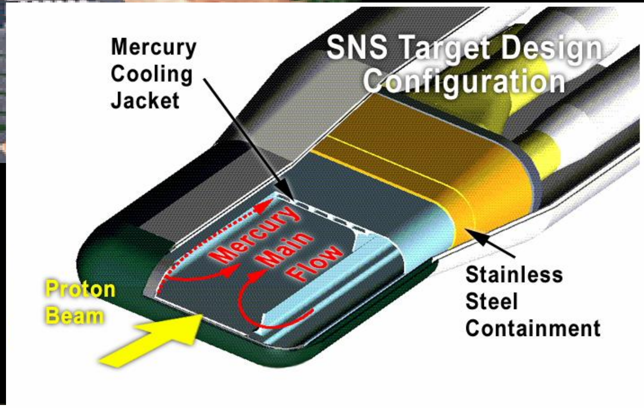
Time Structure – Benefit of a Pulsed Source



- Waiting ~1.2 μs after a pulse to turn on the detector effectively eliminates machine-related backgrounds while retaining high neutrino efficiency (~43%).

- Next pulse arrives in 16,000,000 ns!
  - Turning the detector on for only 10 μs after a pulse reduces cosmic-ray and activation backgrounds by 6×10^{-4}.

Spallation Neutron Source



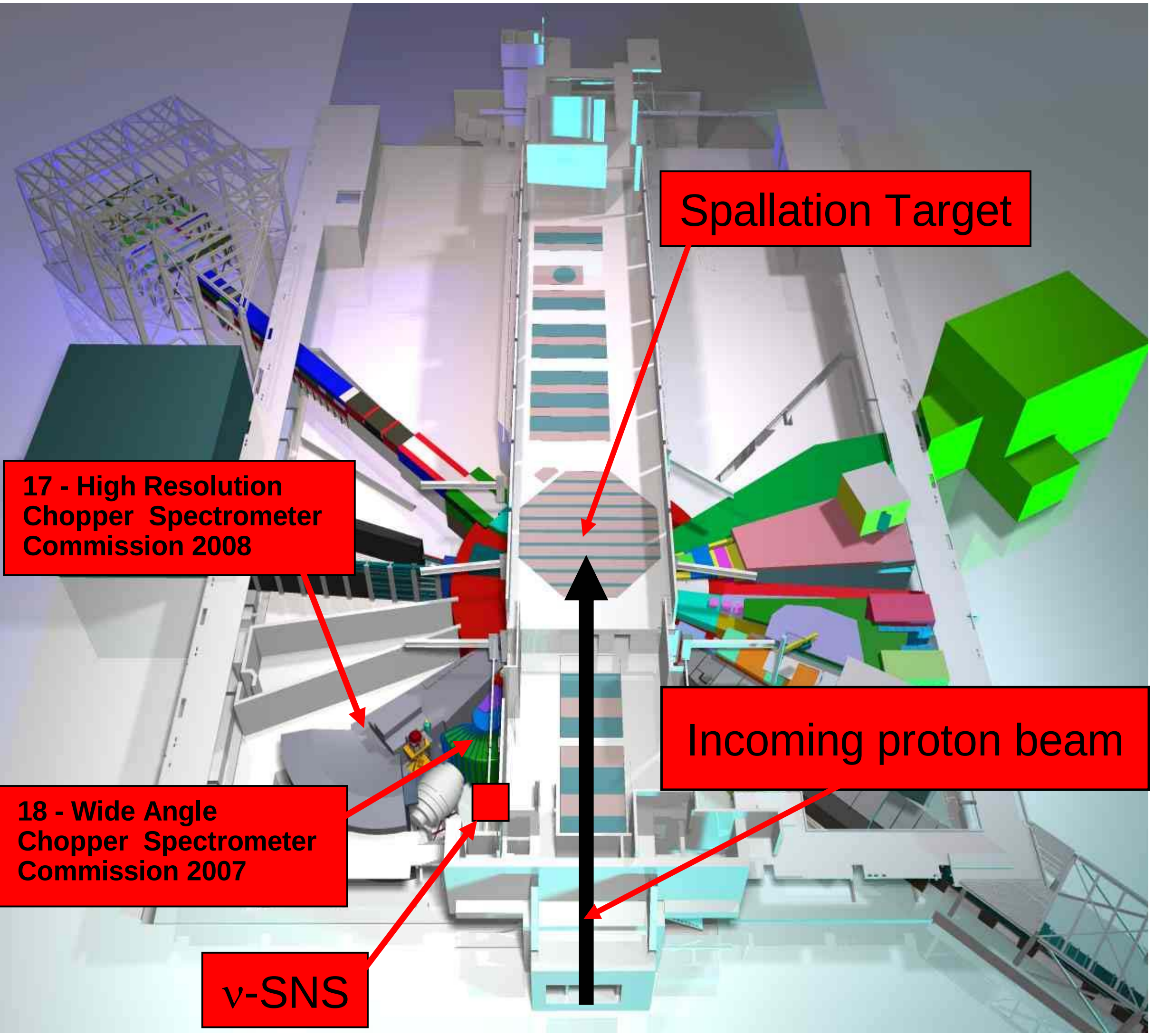
1 GeV beam of protons bombards a liquid mercury target in ~ 500 ns wide bursts

Construction complete in 2006 → 1 MW operation by 2009 → upgrades to 1.4 MW

→ **World's most intense pulsed neutrino source**

~2x10^7 ν/cm^2/s for each flavor @ 1 MW, 20 m from target

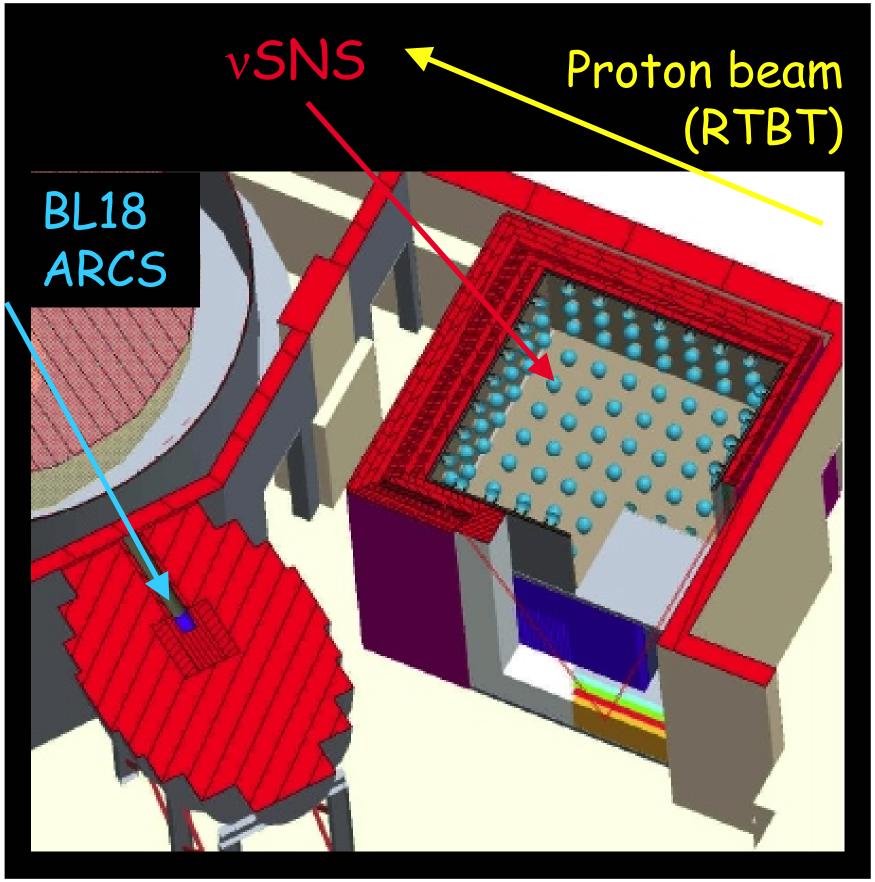
ν-SNS - A Neutrino Facility at the Spallation Neutron Source



- 20 m^2 x 6.5 m (high)
- Close to target ~ 20 m
  $\rightarrow$ 2×10^7 $\nu/cm^2/s$
- θ = 165° to protons
  $\rightarrow$ Lower backgrounds
- In "pit area"
  $\rightarrow$ Greater height available: 6.5 m
  $\rightarrow$ More floor loading: ~500 tons
- Good relationship with SNS management and staff

ν-SNS Facility Overview

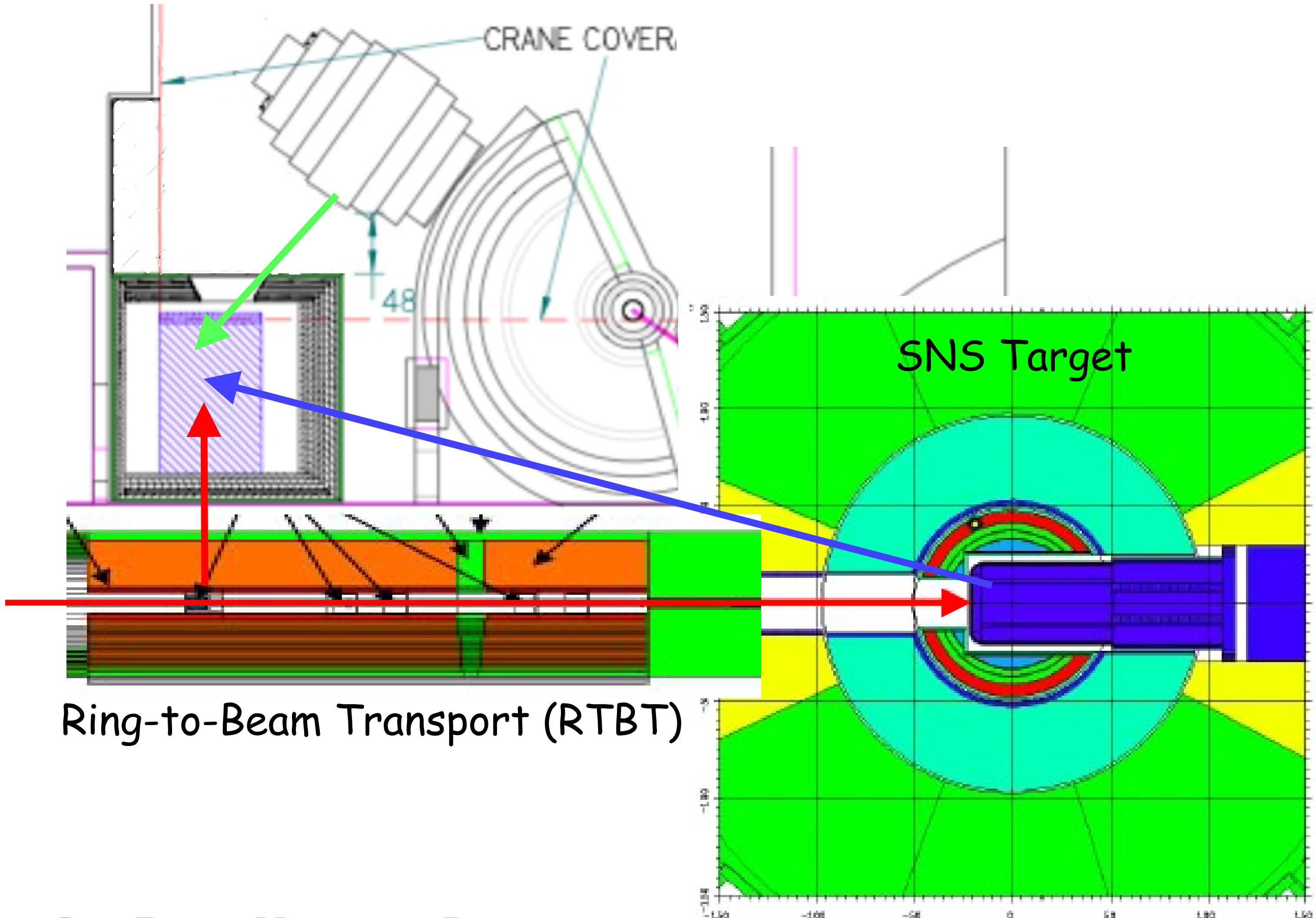
- Heavily shielded facility (fast n!)
- Instrumentable volume ~70 m^3
- Active veto detector for cosmic rays
- Configured to allow two simultaneously, independently operating target/detectors
  - Homogeneous – liquids (C, O, d, …)
  - Segmented – solids (Fe, Pb, Al, …)
  - Detector active elements will be reusable!
- ν-SNS would operate as a user facility with a PAC.
  - Prioritize target nuclei
  - Schedule other experiments
    - Supernovae ν detector prototypes
    - νA coherent scattering (K. Scholberg *et al.*)



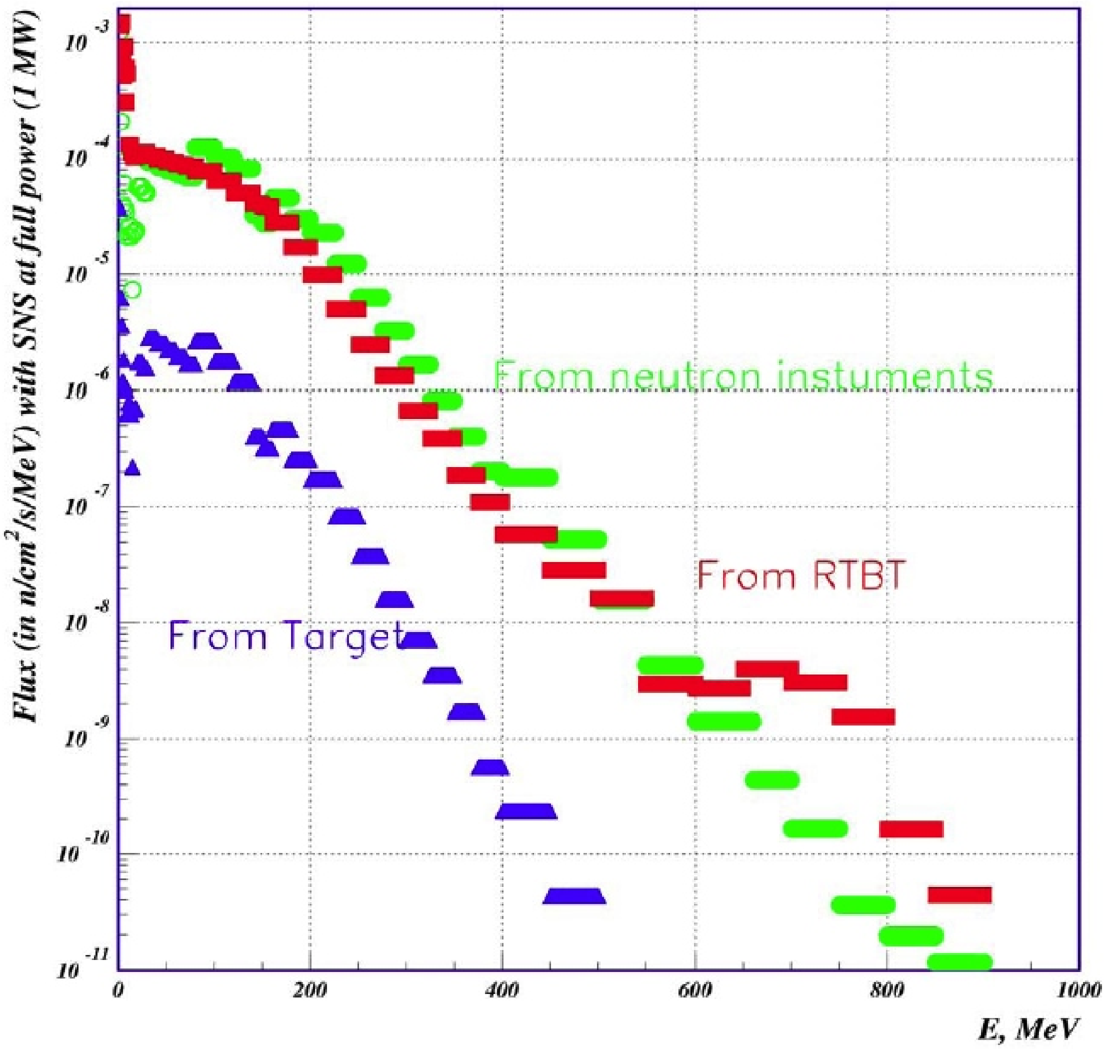
Backgrounds – Sources & Strategies

	Time cut	Shielding	Veto	Particle ID	Beam-off measure & subtract
Cosmic muons	👍		👍	👍	👍
Cosmic neutrons	👍	👍		👍	👍
Long-lived spallation products	👍	👍			👍
SNS neutrons	👍	👍		👍	

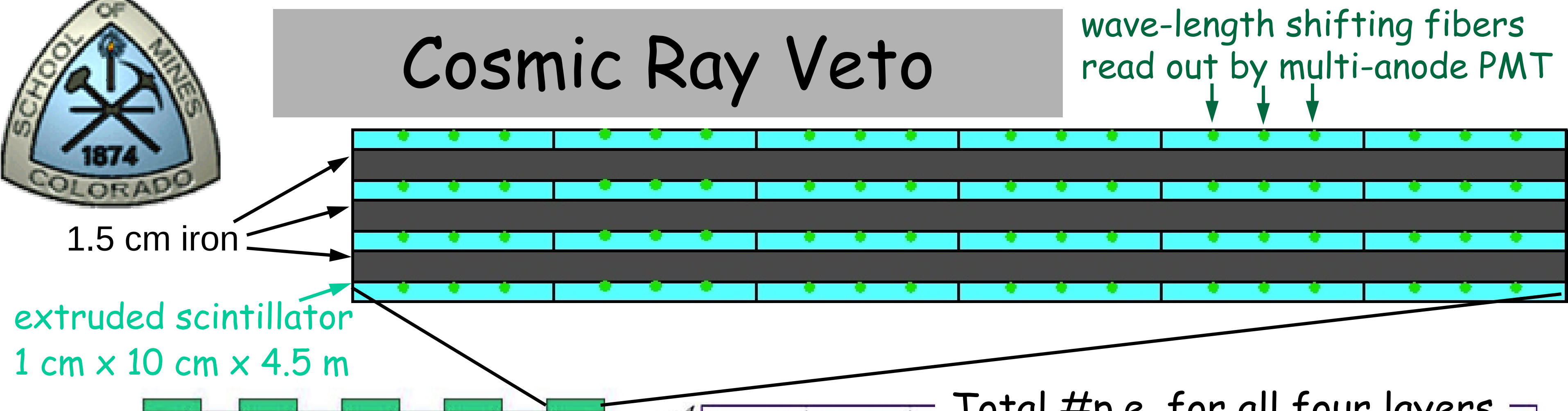
SNS Neutrons

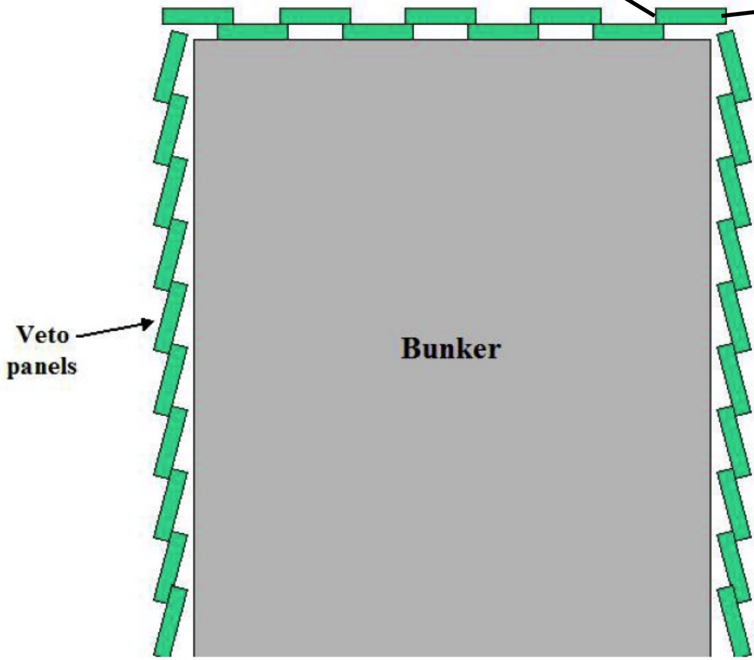


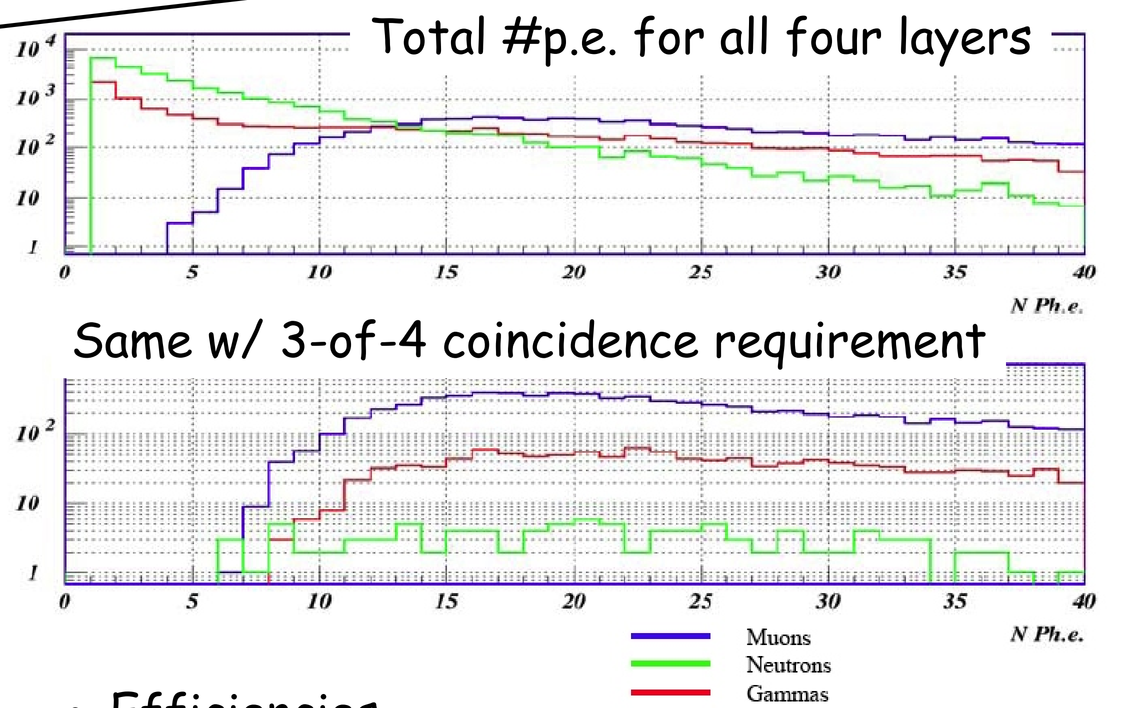
SNS Neutrons



Cosmic Ray Veto







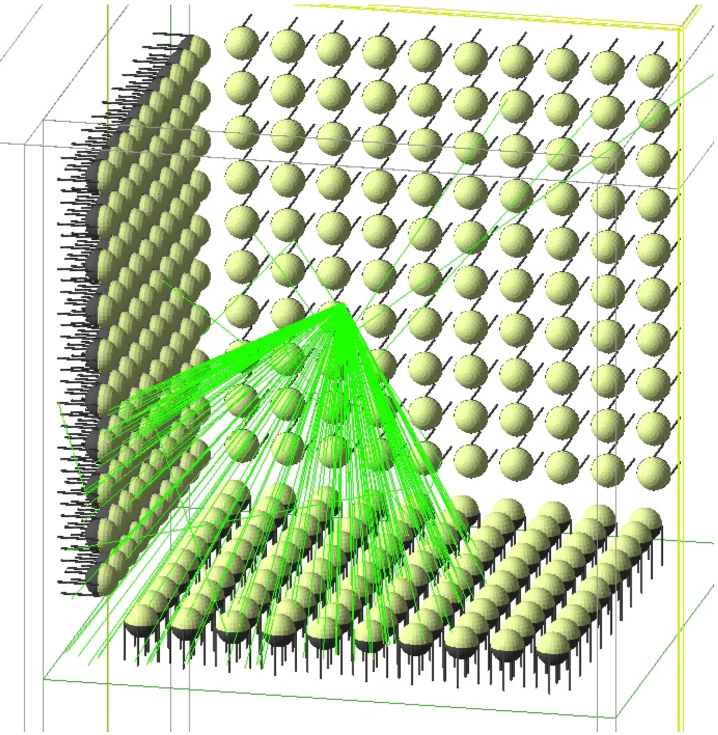
- November 2005
  - 100 planks extruded
  - R&D: fibers, readout, etc.

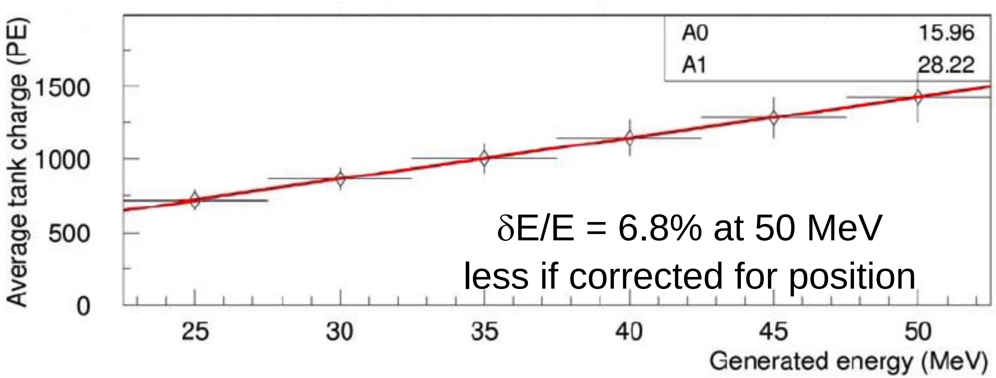
- Efficiencies
  - μ > 99%
  - γ = 0.005%
  - n = 0.07%

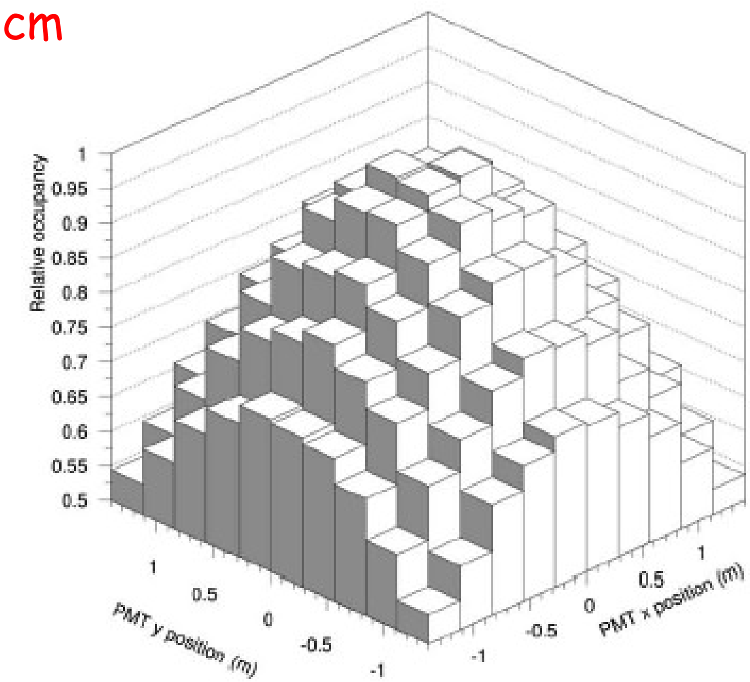
} <<10% of beam pulses vetoed by n or γ

Homogeneous Detector

- 3.5m x 3.5m x 3.5m steel vessel (43 m^3)
- 600 PMT's (8" Hamamatsu R5912)
  - Fiducial volume 15.5 m^3 w/ 41% coverage
- Robust well-understood design (LSND, MiniBoone)
- Current R&D
  - PMT arrangement
  - Neutron discrimination
  - Compact photosensors
- Geant4 simulations ongoing
  - $\delta E/E \sim 6\%$
  - $\delta x \sim$ 15-20 cm
  - $\delta\theta \sim 5^\circ - 7^\circ$

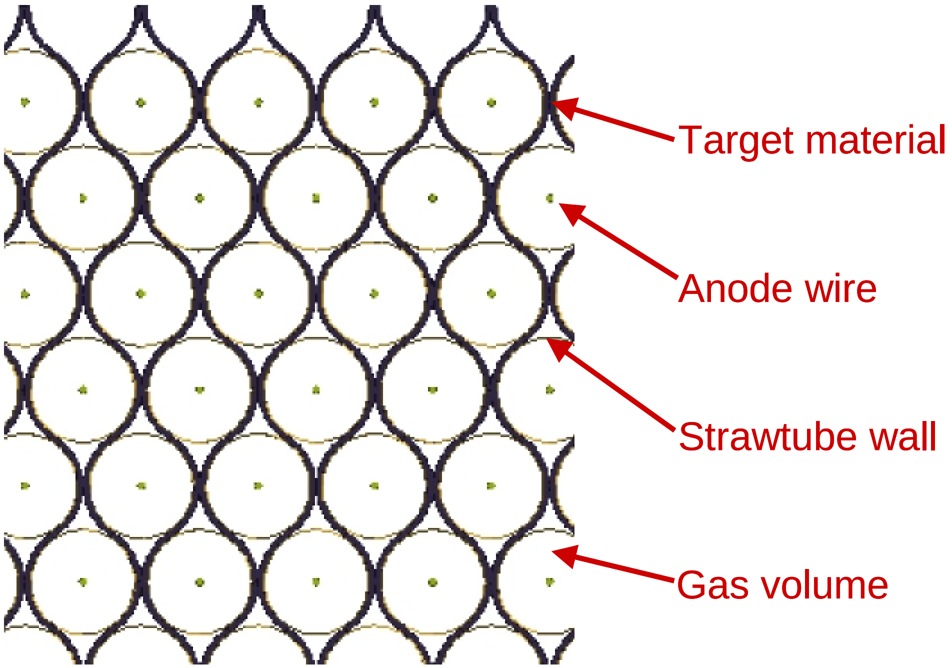




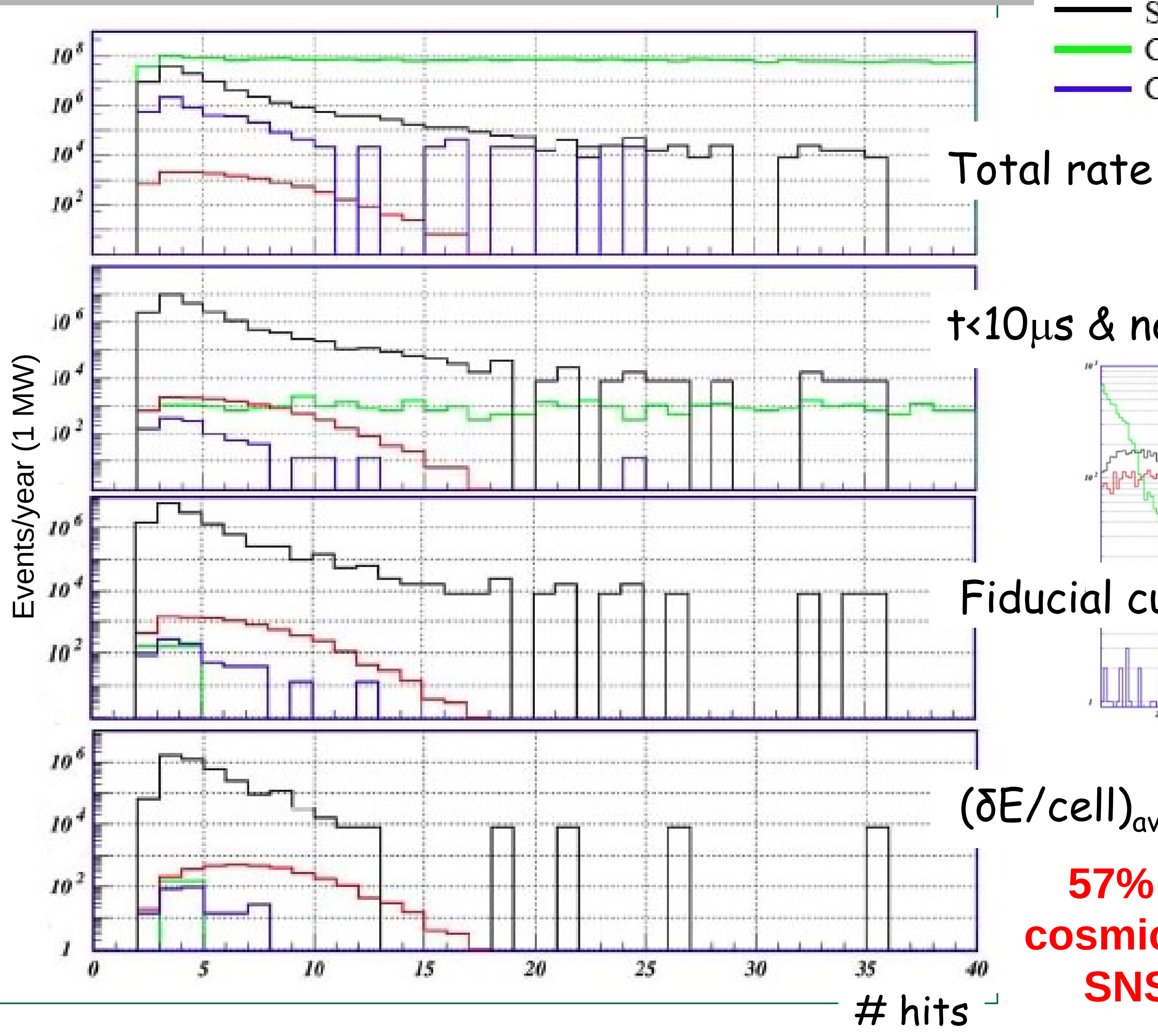


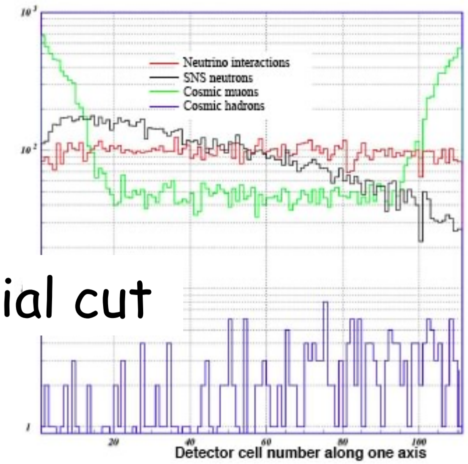
Segmented Detector

- Target - thin corrugated metal sheet (*e.g.* 0.75 mm-thick iron)
  - Total mass ~14 tons, 10 tons fiducial
  - Other good metal targets: Al, Ta, Pb
- Detector
  - 1.4×10^4 gas proportional counters (strawtube)
  - 3m long x 16mm diameter
- 3D position by tube ID & charge division
- PID and energy by track reconstruction
- R&D focus:
  - Prototype testing and parameter optimization
    - Diameters between 10-16 mm
    - Lengths ranging up to 2 m
    - Gases (Ar-CO_2, Isobutane, CF_4)
    - Measure energy, position, time resolution with cosmic muons
  - Simulations to improve the fast neutron discrimination.



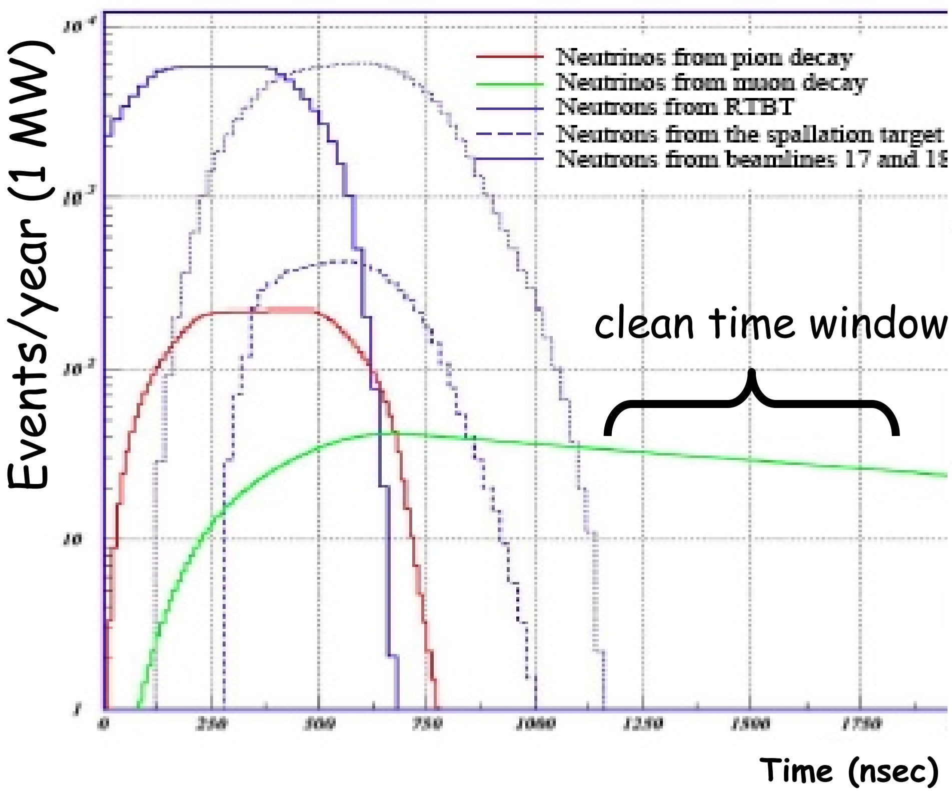
Simulated Performance

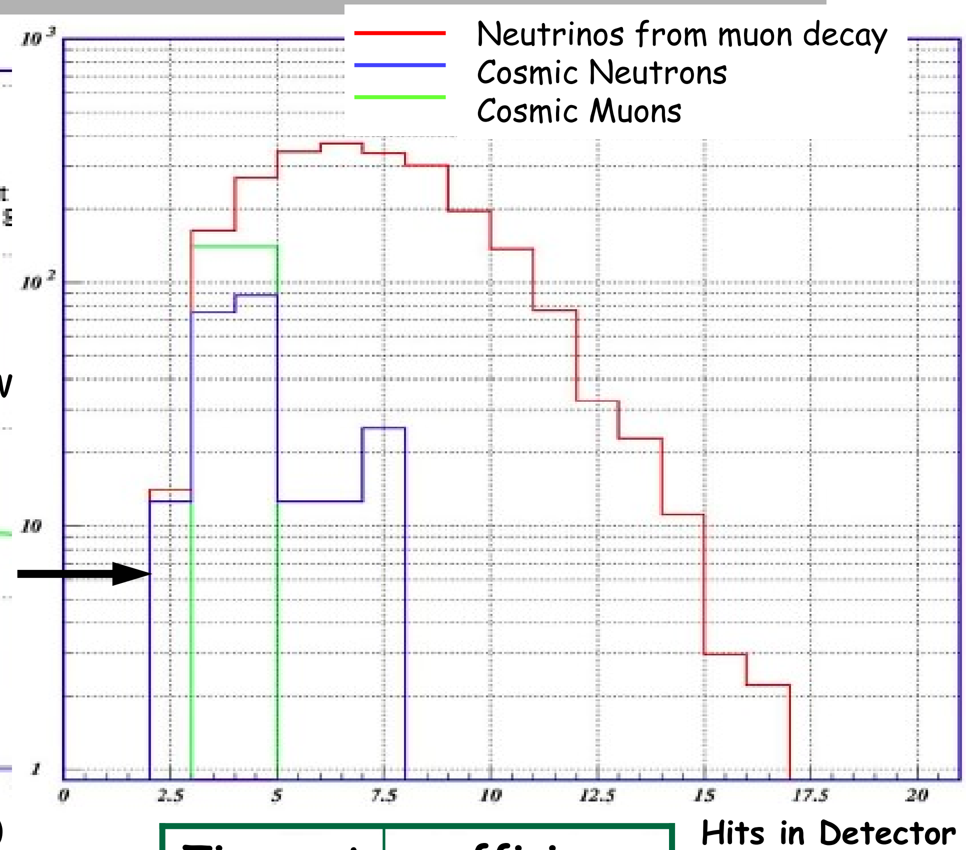




57% ν efficiency
cosmics no problem
SNS neutrons!

Elimination of Facility Backgrounds with a Time Cut





Negligible fast neutrons after 1.2 μs

Time cut (ms)	ν efficiency (%)
1.2-10.0	43
1.5-10.0	37

Statistical Precision

Target	Assumed Cross Section (10^{-40} cm^2)	# Target Nuclei	Raw Counts	Assumed Efficiency	Statistical Significance
Segmented Detector (10 ton fiducial mass)					
Iron	2.5	1.1×10^{29}	3,200	35%	3.0%
Lead	41.0	2.9×10^{28}	14,000	35%	<1.4%
Aluminum	1.12	2.2×10^{29}	3,100	35%	3.0%
Homogeneous Detector (15.5 m^3 fiducial volume)					
Carbon	0.144	5.6×10^{29}	1,000	40%	5.0%
Oxygen	0.08	4.6×10^{29}	450	40%	7.4%

- Number of counts, combined with energy and angular resolution, should allow differential measurements.

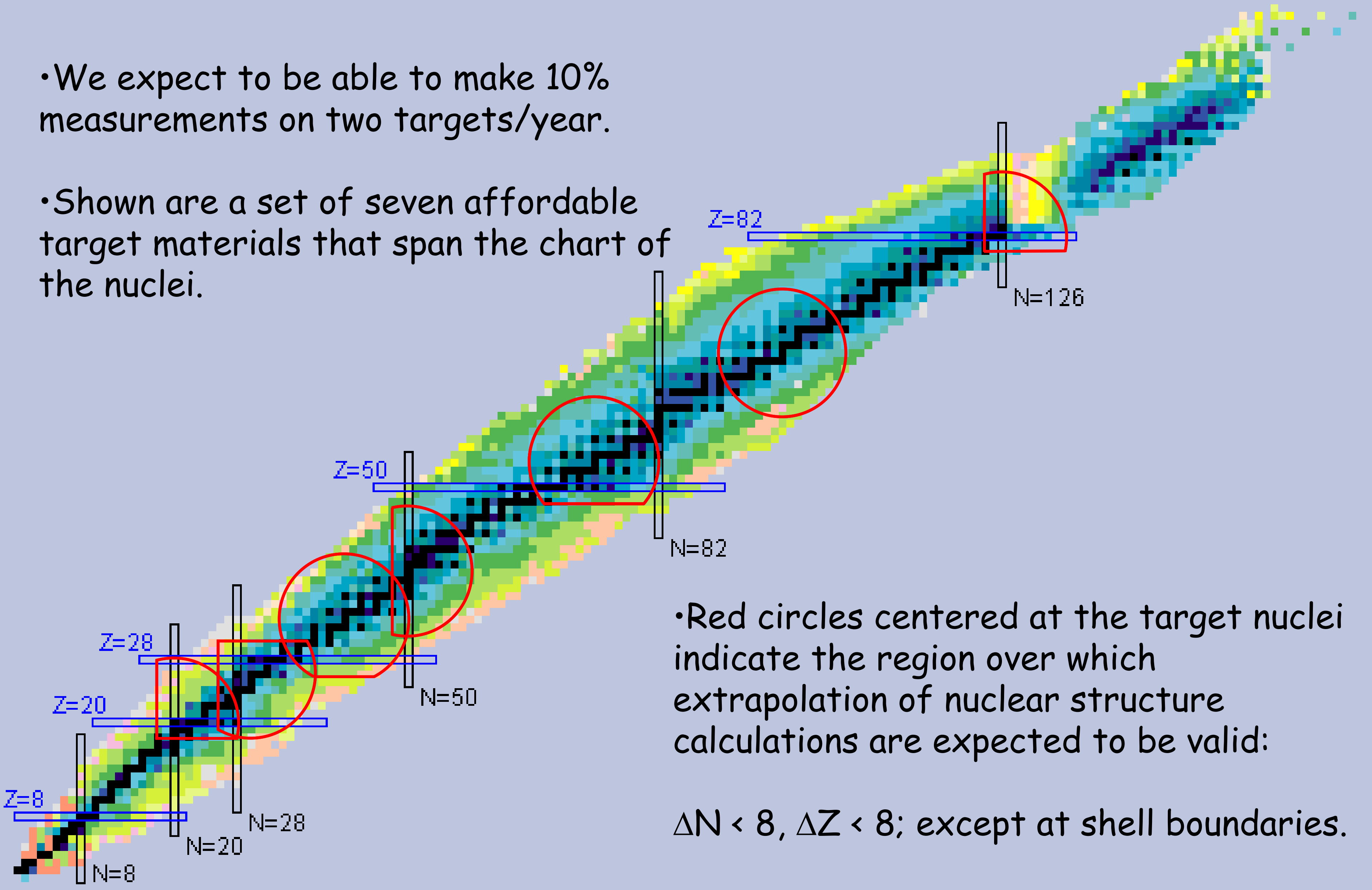
Systematic Precision – Achieving 10%

- Cross section measurements require knowledge of input flux, efficiency.
- Efficiency will be accurately determined via Michel electrons from cosmic muons which stop in the detector while beam is off.
- Input flux is determined by SNS proton flux (well known) and pion production in the thick Mercury target.
  - HARP measurements will help, but thin target.
  - Thick target effects include beam-fragment interactions and pion reabsorption.
  - Some model-dependence remains.
  - Will compare data for ν+C, which has been accurately measured in the past and is theoretically under control.
  - From this determine $\phi_\nu(\phi_p)$ which can be used to normalize normalize other targets.

Broad N/Z Coverage

•We expect to be able to make 10% measurements on two targets/year.

•Shown are a set of seven affordable target materials that span the chart of the nuclei.

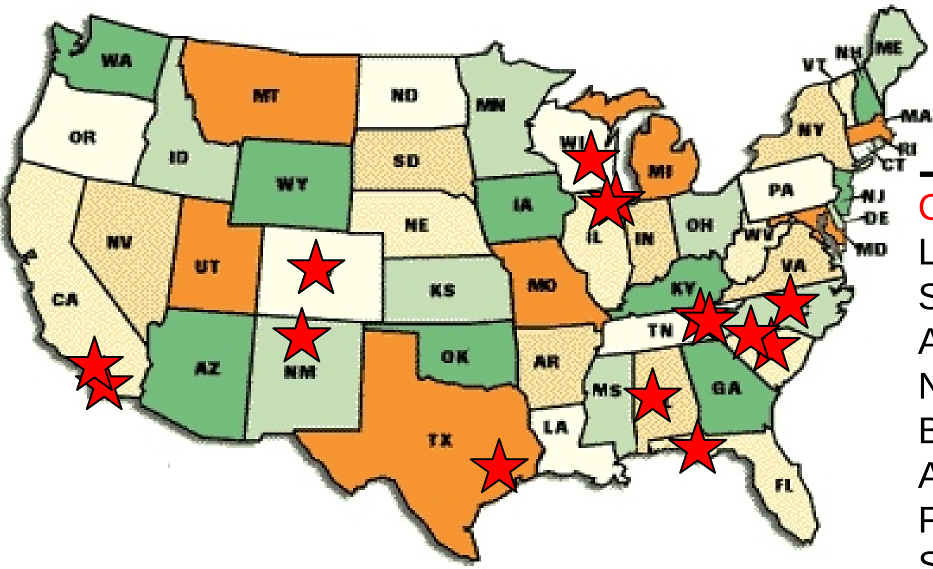


•Red circles centered at the target nuclei indicate the region over which extrapolation of nuclear structure calculations are expected to be valid:

$\Delta N < 8$, $\Delta Z < 8$; except at shell boundaries.

ν-SNS Collaboration

http://www.phy.ornl.gov/nusns



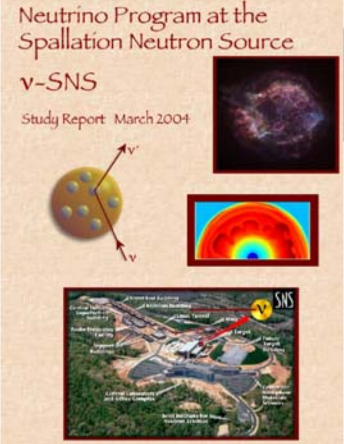
Collaboration Members

19 Institutions
25 Experimentalists
12 Theorists
+ Students

Steering Committee

Chair	Yuri Efremenko (UT)
Liquid Detector	Ion Stancu (Alabama)
Segmented Detector	Yuri Efremenko (UT)
Astrophysics	Tony Mezzacappa (ORNL)
Nuclear Theory	David Dean (ORNL)
Bunker	Vince Cianciolo (ORNL)
Active Veto	Uwe Greife (Colorado School of Mines)
Future Experiments	Richard Van de Water (LANL)
SNS Liaison	Tony Gabriel (SNS)

Institutions: University of Aarhus, University of Alabama, Argonne National Laboratory, University of Basel, California Institute of Technology, University of California - San Diego, Clemson University. Colorado School of Mines, Fermi National Accelerator Laboratory, Florida State University, University of Houston, JINR-Dubna, Los Alamos National Laboratory, North Carolina State University, Oak Ridge National Laboratory, University of South Carolina, University of Tennessee, University of Wisconsin



OAK RIDGE NATIONAL LABORATORY

Associate Laboratory Director
for the Spallation Neutron Source

Date: August 27, 2004

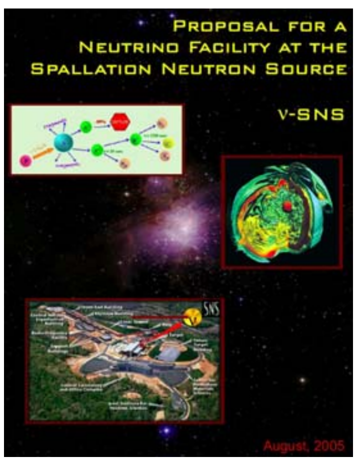
To: Professor Yuri Efremenko

c: I. S. Anderson, J. B. Roberto, G. R. Young

From: Thomas E. Mason, 8600, MS-6477 (241-1499)

Subject: **Neutrino Program at the Spallation Neutron Source**

Following receipt of your Letter of Intent to establish a Neutrino Program at the Spallation Neutron Source (SNS), we have conducted a review of the submission, enlisting external expertise to supplement our own appraisal of the feasibility of this proposal as well as discussions with our Advisory Committees. I am attaching two referee reports that informed our assessment of the scientific promise of this proposal. Both referees felt that it would be appropriate to proceed with a full proposal. In addition, our own review of the impact of the program indicates that it can be accommodated at SNS provided the footprint and floor loading are coordinated with the Experimental Facilities Division to insure there is no unacceptable compromise of access to neighboring instruments. Based on this input there is sufficient merit to the Letter of Intent and the scientific program it describes to warrant proceeding with a full proposal. The full proposal should document in a more detailed way the design of the proposed instrumentation, its scientific capability, and how its makes effective use of the



Timeline

March 2004
Study report completed
Letter of Intent to SNS

August 2004
Green light from SNS

August 2005
Proposal submitted
to DOE Nuclear Physics

Project Cost

Item	***$M***
Bunker	2.8
Veto	1.4
Segmented Detector	1.6
Homogeneous Detector	1.6
Utilities	0.3
ESHQ	0.1
DAQ	0.3
Project Management	0.4
Total	**8.6**

Proposed Schedule

CD1	9/07
Construction	FY09-FY11
Operations begin	FY12

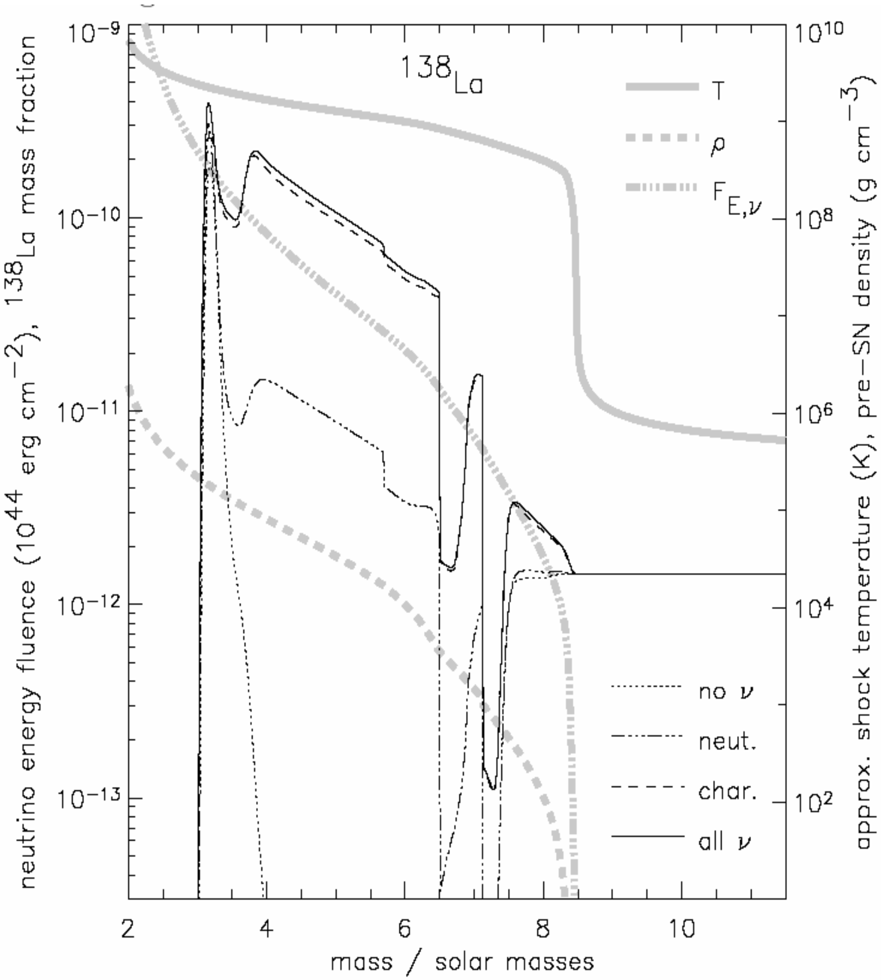
Summary

- The SNS provides us with a unique opportunity for measuring νA cross sections at energies relevant for supernovae and nuclear structure
- We have proposed to build a shielded facility and two simultaneously operating neutrino detectors
  - Experiments likely to include C, O, d, Fe, Al, Pb,…
  - Cross section measurements to < 10% accuracy in 1 year!
  - Interesting SM tests can be made for "free"
  - Facility can also house alternative experiments
    - Calibration of supernova neutrino detector elements
    - νA coherent scattering
    - …

Backup Slides

Neutrino Nucleosynthesis

- Combination of neutrino spallation reactions and the subsequent passing of the supernova shock may produce several isotopes that are difficult to make in any other astrophysical circumstance.
- These isotopes include ^{11}B, ^{19}F, ^{138}La, and ^{180}Ta.

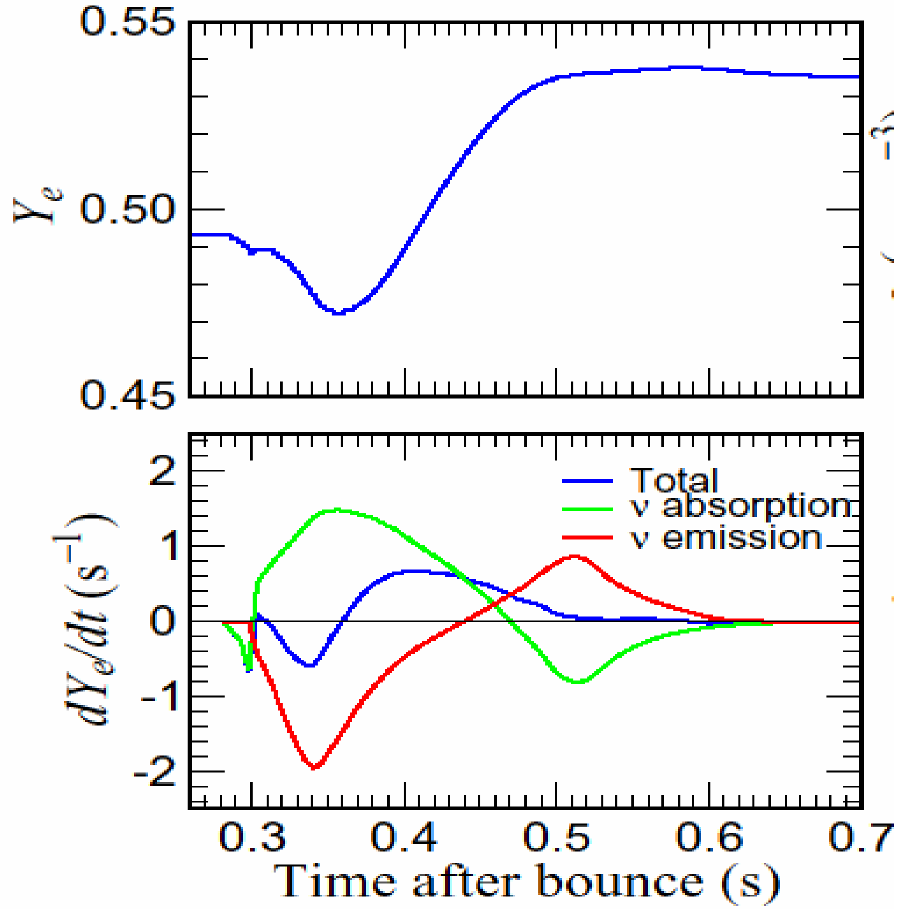


Heger, Kolbe, Haxton, Langanke, Martínez-Pinedo & Woosley 2004

Explosive Nucleosynthesis

- The competition between ν_e, $\bar{\nu}_e$, e^- & e^+ captures on nucleons and heavy nuclei sets the electron fraction in the iron-rich ejecta.

- These processes also heat the matter affecting the α-richness of the ejecta and therefore the abundances of many of the isotopes which can be detected by γ-ray telescopes.



Hauser, Martinez-Pinedo, Hix, Liebendörfer, Mezzacappa & Thielemann 2004

Neutrinos and the *r*-process

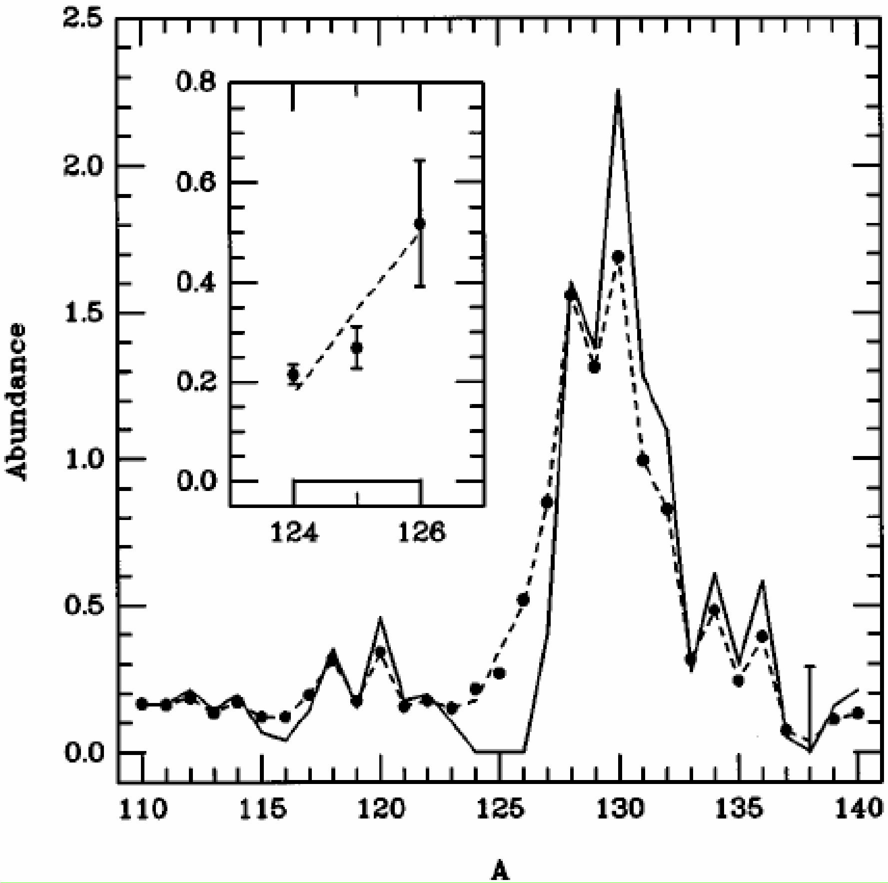
•Large neutrino fluxes are present at all plausible astrophysical sites for the *r*-process

•Interactions between ν's and nuclei have both positive and negative effects on the *r*-process.

- Neutrinos interacting with gas dominated by free neutrons and α particles will decrease the neutronization, quenching the *r*-process.

- Neutrino captures on waiting point nuclei can replace β decays, accelerating the *r*-process.

- Neutrino interactions can liberate nucleons, shifting abundances down from the peaks.



Y.-Z. Qian *et al.*, Phys. Rev. **C55**, 1532 (1997).

Cosmic Ray Backgrounds

- SNS time structure suppresses cosmic event rate by 6×10^{-4}
- 1.5×10^{5} cosmic muons/day
  - 2.9% of beam spills contaminated by cosmic muons
  - Nearly all are easily discriminated by detectors and/or veto

  <u>However, some background contribution remains</u>:
    - Muon does not fire veto or detector
    - Produces fast neutron in shielding
    - 99% veto $\rightarrow$ 30 fast neutrons/day
    - Must be further reduced by detector signatures
    - Will be very accurately characterized via beam-off data
- 3×10^{3} cosmic-ray neutrons/day
  - Only reduced by shielding $\rightarrow$ sets scale for bunker

  <u>Goal: reduce this flux to 30/day (equal to irreducible $\mu\rightarrow n$ contribution)</u>
    - 1-m-thick steel ceiling reduces flux by 10^{2}
    - Given floor loading limit, this leaves ~40 m^3 of shielding for sides

      $\rightarrow$0.5-m-thick walls on average

Spallation Products

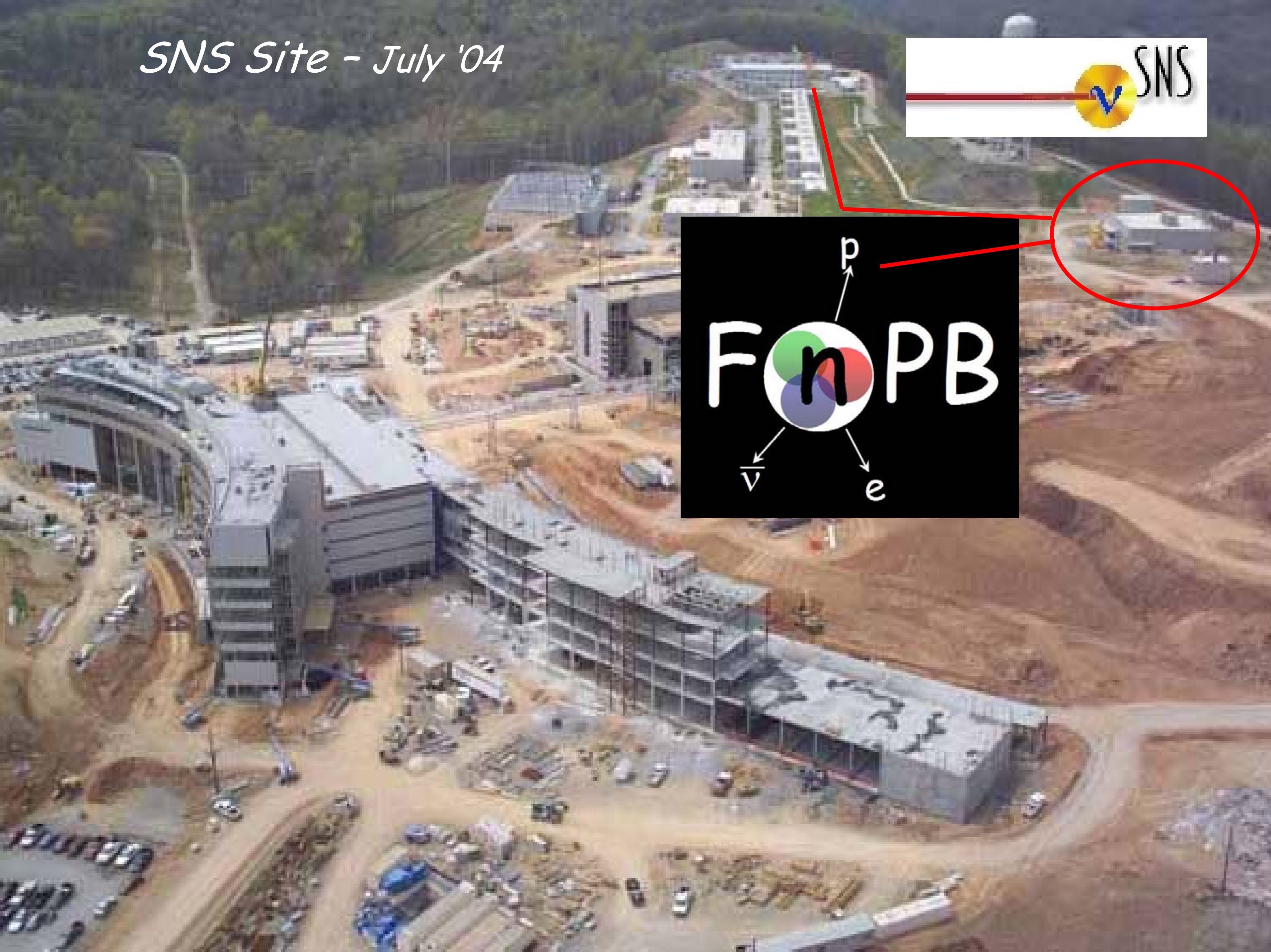
- Cosmic-ray muons and SNS neutrons can generate long-lived radioactive isotopes like ^{12}B in liquid scintillator or ^{16}N in water.

C. Galbiati and J.F. Beacom, Phys. Rev **C72**, 025807 (2005).

- Estimated rate ~10(μ)+20(n)/day.
- Those isotopes have lifetimes long enough that it is impractical to use information from the parent to tag them.
- However:
  - *Q*-value of their decay products is in the range of 10-15 MeV, which is below the average lepton energy from neutrino interactions.
  - In addition, we can accurately measure their rate during periods with beam off and statistically subtract them.

SNS Pics from 12/04

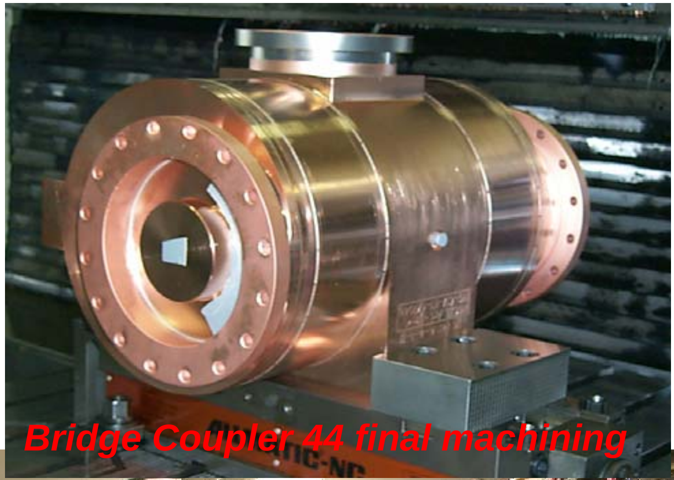
SNS Site – July '04



Drift Tube Linac

- System includes 210 drift tubes, transverse focusing via PM quads, 24 dipole correctors, and associated beam diagnostics
- All tanks have been assembled, RF tuned, installed and now beam commissioned

Coupled-Cavity Linac



- *System consists of 48 accelerating segments, 48 quadrupoles, 32 steering magnets and diagnostics*
- *All CCL modules have been built, RF tuned, installed and are now being Beam Commissioned.*

Superconducting Linac

- 17 of 23 cryomodules constructed
- 10 of 11 med-β cryomodules installed in tunnel
- 3 of 12 High- β cryomodules installed in tunnel
- Cavities are exceeding gradient specifications

Medium beta cavity

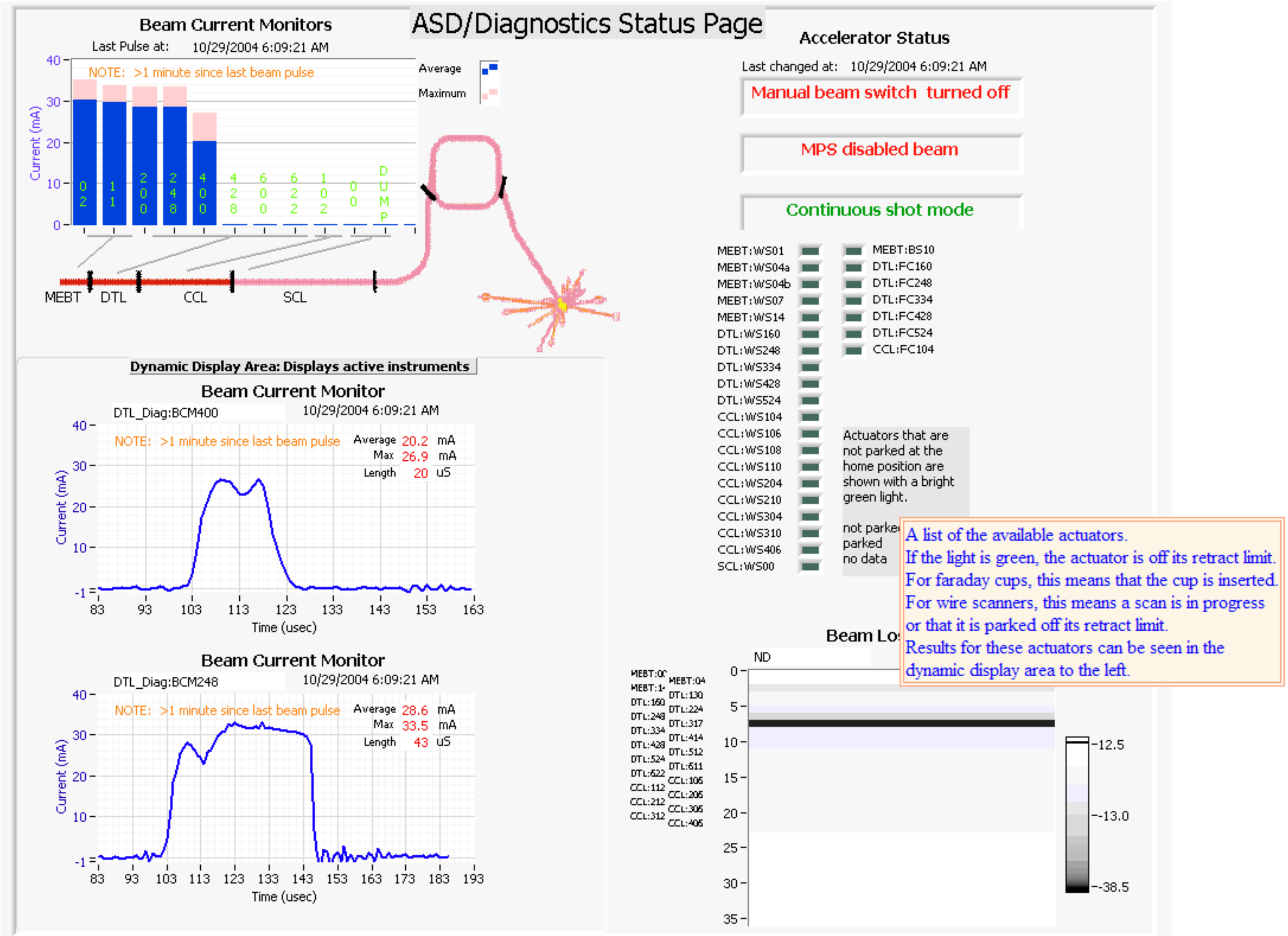
High beta cavity

High-Power RF Installation Progress

- All four CCL systems are complete.
- 81 of 81 SCL klystrons installed.

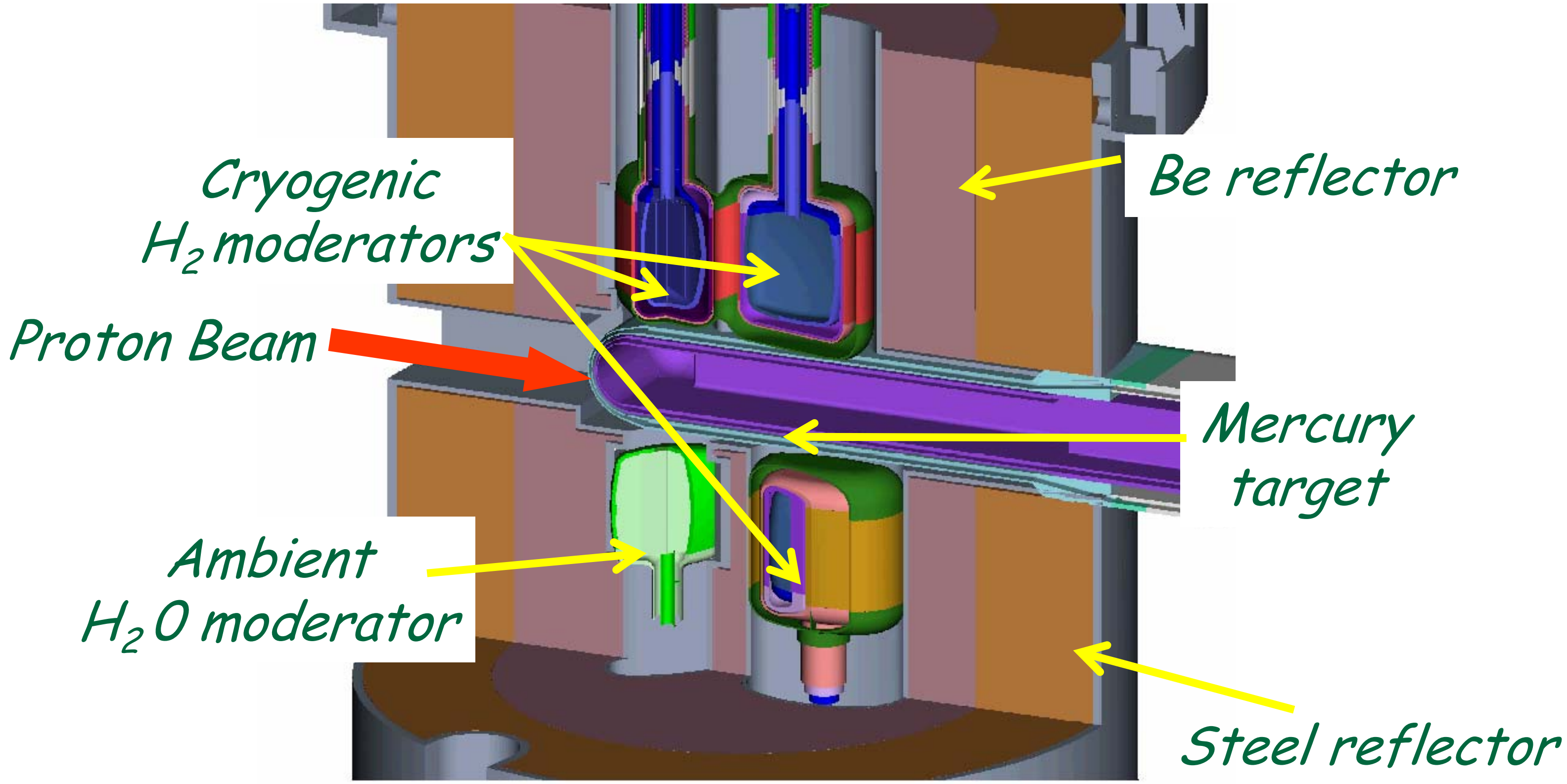
10 tubes turned over to operations

Accelerator Status WWW Page!



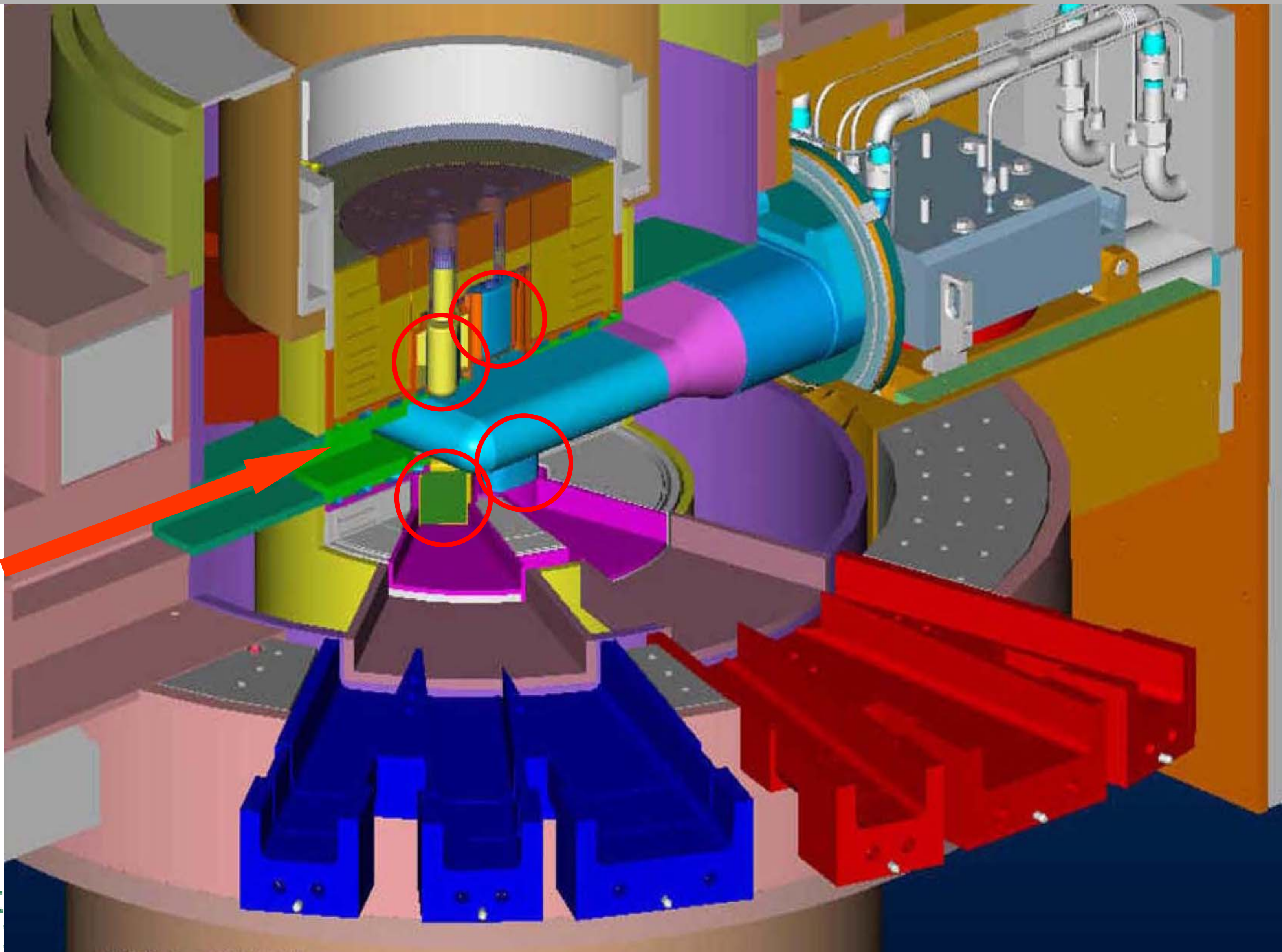
Ring Component Installation

Target, Reflectors, Moderators

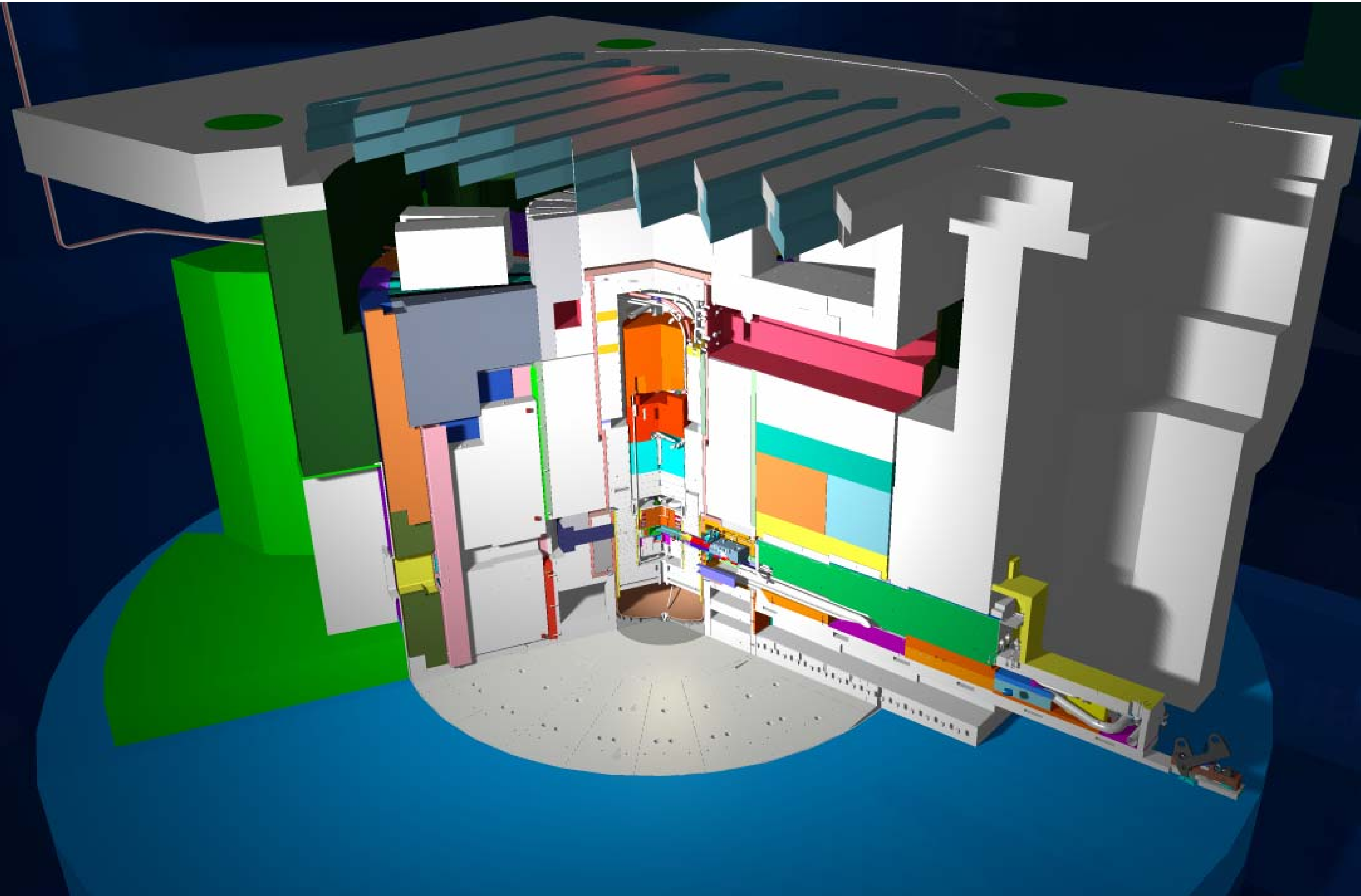


- 16 tons Hg; 360 gallons/min.
- Mercury chosen due to:
  - High-Z.
    - Lots of neutrons/proton.
  - Liquid nature.
    - Doesn't suffer radiation damage.
    - Better at dissipating heat.

A Different View of the Target, Moderators and Beamlines



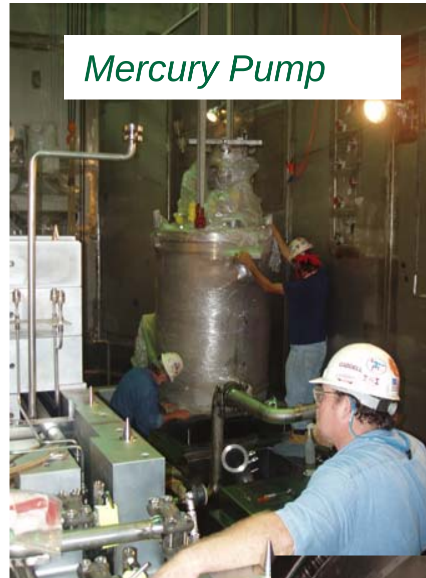
Target Monolith



Target Installation

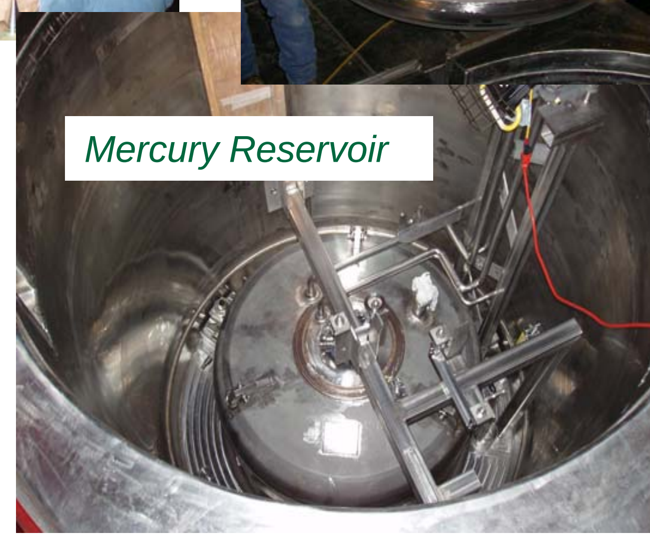

Target Carriage


Target Cart Rails


Mercury Pump


Mercury Collection Basin


Mercury Heat Exchanger


Mercury Reservoir

Target Monolith